ICTAM 2008
ADELAIDE

XXII International Congress of Theoretical and Applied Mechanics

Abstracts book

Edited by Jim Denier, Matthew Finn and Trent Mattner

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Preface

The International Congress of Theoretical and Applied Mechanics, held in Adelaide, Australia is the twenty-second ICTAM. The idea of holding regular congresses devoted to the field of mechanics can be traced back to a conference on problems of fluid mechanics, held in Innsbruck, in 1922, and organized by four of the founding fathers of modern fluid dynamics, C. W. Oseen, T. Levi-Civita, T. von Kármán, and L. Prandtl. Although it attracted only thirty people, this conference provided the spark that led to the first ICTAM held in Delft in 1924 and organised by J. M. Burgers and C. B. Biezeno. This conference was so fruitful that the organisers decided to arrange similar meetings in the future, every four years, and to extend the scope of the future meetings to include solid mechanics.

The organisation of successive congresses was placed in the hands of a Congress Committee. During the sixth congress, held in Paris, the idea arose of a more permanent organization to look out for the world interests in the mechanical sciences. Thus IUTAM, the International Union of Theoretical and Applied Mechanics, was formed on 26 September 1946. In 1947, IUTAM became a member of ICSU, the International Council of Scientific Unions, itself founded in 1931. The highest authority of IUTAM is the General Assembly, with delegates from the Adhering Organizations, each of which is affiliated with a national learned society in a given country.

Contemporary mechanics incorporates fundamental problems from pure science and has strong links into modern technology. It pervades many areas of scientific endeavour, including oceanography, physical chemistry, biology, medicine, geophysics and astrophysics. We hope that this meeting will continue to spread the ever-expanding pool of knowledge in the mechanical sciences and continue to contribute to the advancement of mutual human understanding.

The 22nd International Congress of Theoretical and Applied Mechanics comes to Adelaide, Australia at the invitation of the Australian Academy of Science, in conjunction with the University of Adelaide and the Flinders University of South Australia.

We hope that this, the first IUTAM Congress to be held in the Southern Hemisphere, will continue to stimulate a new generation of researchers to seek out the solutions to many of the challenging problems facing us, and continue to stimulate developments in this area. We would like to thank all the contributors of this Congress. We are sure that your contribution of up to the minute research will make the Congress a roaring success. Welcome to Adelaide!

Ernie Tuck

Jim Denier

Adelaide, August, 2008

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Contents

Sessions on solid mechanics

Session involving both fluid and solid mechanics

Introduction

The scientific program consists of plenary opening and closing lectures, sectional lectures, prize lectures, mini-symposia, and contributed papers presented in lecture and seminar presentation sessions. These are intended to cover all aspects of mechanics. This volume contains 965 papers which have been drawn from the oral and the seminar presentations of the congress. Each paper consists of a printed Short Abstract and a Short Paper recorded on the enclosed CD-ROM. Obviously, this book contains papers that were submitted over six months ago. As a result the work presented at the congress may deliver more recent data and evaluative work than had been possible to allude to in the publication.

All contributed papers were peer reviewed. Recommendations were received from Pre-selection Committees of the National Committees of nine countries: Canada, France, Germany, Japan, China, Poland, Russia, UK and USA. Moreover, recommendations were received from the Chairs of the Mini-Symposia and of the Pre-nominated Sessions. Finally, the International Papers Committee reviewed each short paper, paying careful attention to the recommendations of the pre-selection committees. Accordingly, of the 1517 eligible submissions only 1322 contributions were invited by the IPC to be presented at the Congress.

Finding your way around

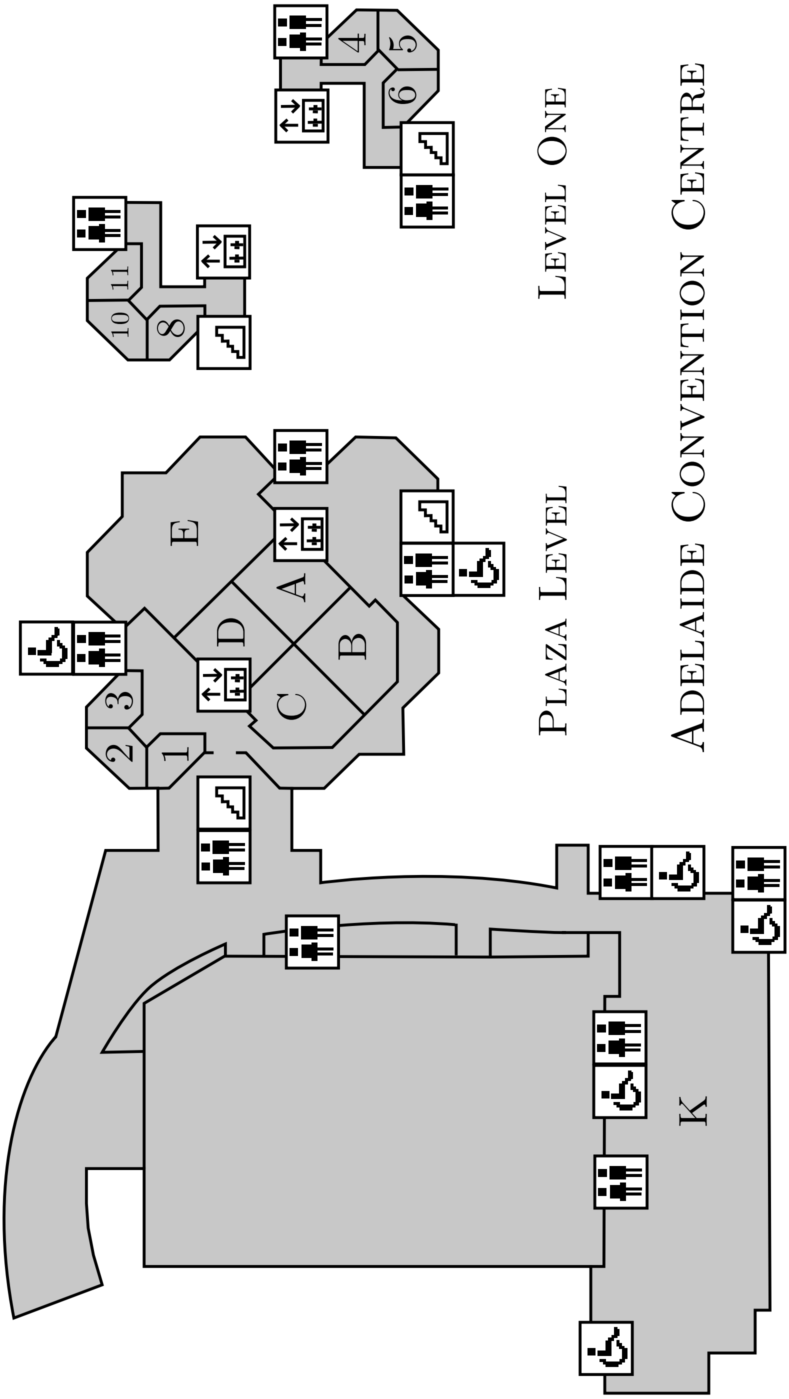
The scientific presentations will take place in the Halls and Meeting Rooms of the Adelaide Convention Centre, shown on the building layout on the following page. The rooms are divided between the lower Plaza Level and upper Level One, with both stair and lift access between the floors.

Halls A–E are equipped with removable partition walls and will be reconfigured during the meeting to accommodate both the plenary lectures and some of the parallel sessions. The Meeting Rooms 1–11 beside the Halls and on Level One will also be used for the parallel sessions. Please note that there is no direct access between rooms 4–6 and 8–11 without returning to the Plaza Level. Hall K is a short walk through the centre from the other rooms, and will be the central meeting place for the week, hosting the **Get-Together Party** (Sunday 18:00), coffee breaks and all poster displays.

The **Welcome Reception** (Monday 19:00) is included in the registration for all of our participants, and will be held at the South Australian Museum. The Museum is located on North Terrace to the east of the Convention Centre. The distance is approximately 700m, and is a pleasant walk past the Parliament of South Australia, and the State Library. You will find the Museum marked on the map on page 3.

Delegates who have purchased a ticket for the **Congress Banquet** (Thursday 19:00) will need to make their way to the Hilton Adelaide, located on the west side of Victoria Square in the centre of the city. A tram runs east from the Convention Centre along North Terrace and then south down King William Street to directly outside the Hilton. The tram is free for this journey, but the distance is only 1300m so you may prefer to walk. You will also find the Hilton marked on the map on page 3.

Adelaide has an abundance of **restaurants** and **bars**. Two very popular places to dine out are Rundle Street and Gouger Street, both of which are indicated on the map. If you wish to explore the city centre and beyond in more detail, you may find the maps in your satchel useful, and there is a **tourist information** centre located on Rundle Mall, the main shopping street.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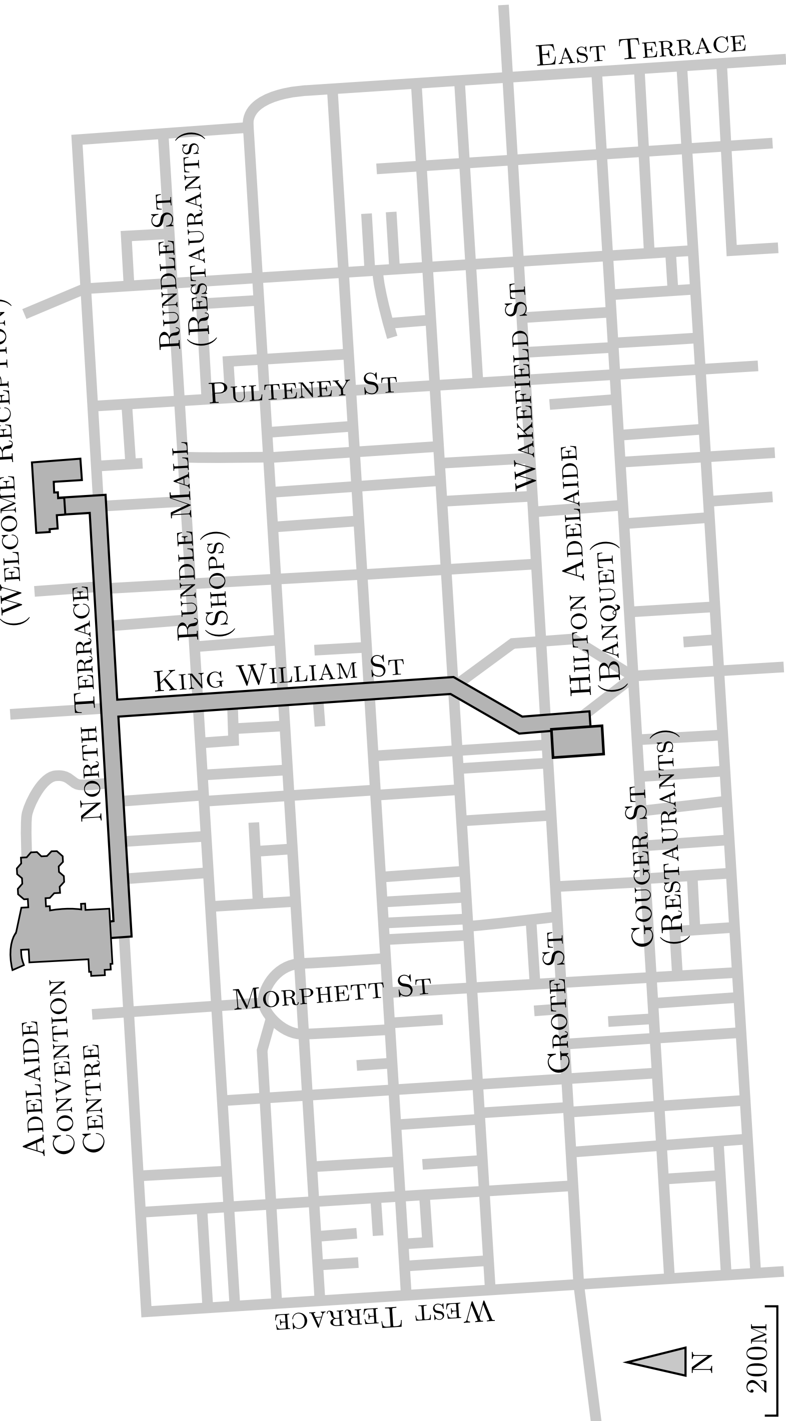
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Rundle St (Restaurants)
South Australian Museum (Welcome Reception)
Pulteney St
Wakefield St
Rundle Mall (Shops)
Hilton Adelaide (Banquet)
Adelaide City Centre
North Terrace
King William St
Gouger St (Restaurants)
Grote St
Morphett St
Adelaide Convention Centre
West Terrace
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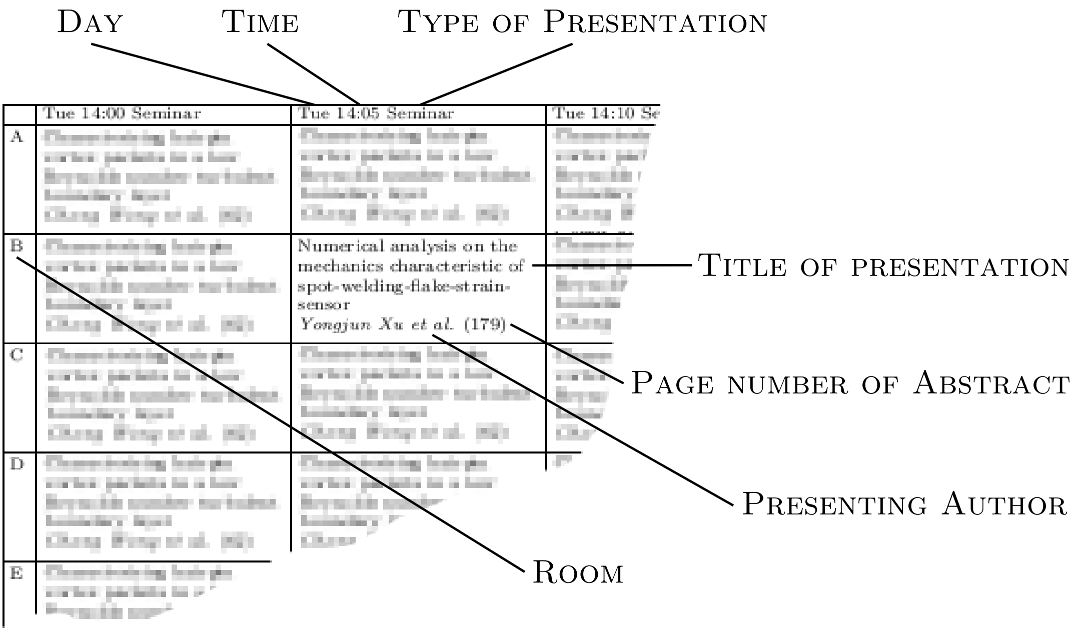
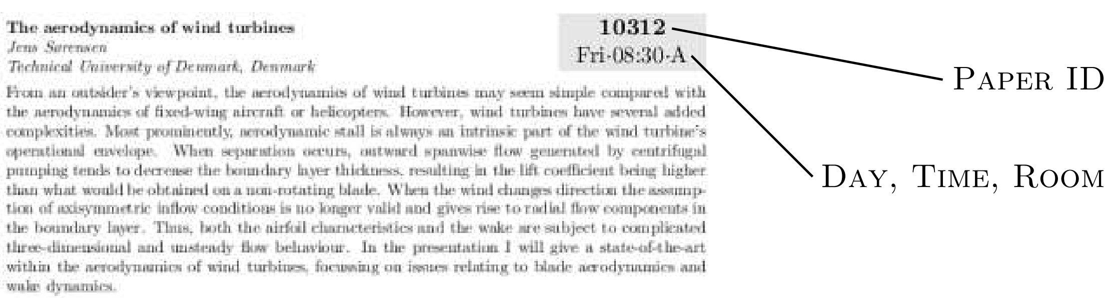
200m

Planning your congress

A timetable for the scientific program is provided on the following pages. Naturally, with 965 papers, the timetable must be spread across several pages. To assist with forming your own timetable for the meeting, and to reduce the need to cross reference between pages, the timetable is arranged so that all events occuring at a given time appear in one column, and all on the same page. The rows of the timetable correspond to the rooms at the Convention Centre, indicated on the map on page 2. Each slot in the timetable provides the title of the paper, the presenting author and the page on which the full abstract is located.



The titles, abstracts, full lists of authors, and presenting author affiliations are given in the main sections of this book, after the timetable. The papers are grouped according to session, and within each session the papers are listed in chronological order. Beside each abstract is an information box which provides the day, time and room for the presentation. The ID number for the paper is also given, and this may be used to access quickly the full PDF paper from either the congress web site, or the CD-ROM proceedings.



Congress timetable

	Sunday 24 August	
15:00–18:00	Registration	Hall K
18:00–19:00	Get-Together Party	Hall K
	Monday 25 August	
09:00–10:00	Opening Ceremony	Hall E
10:00–11:00	Opening Lecture	Hall E
11:00–13:00	Mini-symposia lectures	Halls A–E
13:00–14:00	Lunch	
14:00–16:00	Lecture sessions	Halls A–E, Rooms 1–11
16:00–16:25	Coffee break	Hall K
16:25–17:45	Lecture sessions	Halls A–E, Rooms 1–11
19:00–21:00	Welcome Reception	South Australian Museum
	Tuesday 26 August	
08:30–09:15	Sectional lectures	Halls A–D
09:15–09:55	Mini-symposia lectures	Halls A–D
09:55–10:40	Coffee break	Hall K
10:40–12:40	Lecture sessions	Halls A–E, Rooms 1–11
12:40–14:00	Lunch	
14:00–15:15	Seminar sessions	Halls A–E, Rooms 1–11
15:15–16:00	Poster viewing and coffee	Hall K
16:00–17:40	Lecture sessions	Halls A–E, Rooms 1–11
	Wednesday 27 August	
08:30–09:25	Prize lectures	Halls A–E
09:25–10:10	Sectional lectures	Halls A–D
10:10–10:40	Coffee break	Hall K
10:40–13:00	Lecture sessions	Halls A–E, Rooms 1–11
13:00–17:00	Excursions	
	Thursday 28 August	
08:30–09:15	Sectional lectures	Halls A–D
09:15–10:35	Lecture sessions	Halls A–E, Rooms 1–11
10:35–11:00	Coffee break	Hall K
11:00–13:00	Lecture sessions	Halls A–E, Rooms 1–11
13:00–14:00	Lunch	
14:00–15:10	Seminar sessions	Halls A–E, Rooms 1–11
15:10–16:00	Poster viewing and coffee	Hall K
16:00–17:00	Lecture sessions	Halls A–E, Rooms 1–11
19:00–22:00	Congress Banquet	Adelaide Hilton
	Friday 29 August	
08:30–09:15	Sectional lectures	Halls A–E
09:15–10:35	Lecture sessions	Halls A–E, Rooms 1–11
10:35–11:00	Coffee break	Hall K
11:00–12:20	Lecture sessions	Halls A–E, Rooms 1–11
12:25–13:25	Closing Lecture	Hall E
13:25–14:25	Lunch	

		Mon 10:00 Lecture		Mon 11:00 Lecture
A			**Classical and quantum vortex rings** ▶	Classical vortex rings, with and without swirl *Keith Moffatt* (70)
B			**Mechanics of colloidal systems** ▶	Single particle motion in colloids: from microrheology to osmotic propulsion *John Brady* (65)
C			**Cohesive zone models of fracture and failure** ▶	Modelling of bone failure by cohesive zone models: nano- and microscale *Thomas Siegmund* (46)
D			**Multi-component materials, modelling on different scales** ▶	Multi-scale analysis of polycristalline metals and composites *Jean-Louis Chaboche* (53)
E	**Opening Lecture** ▶	The role of mechanics in advancing thermal barrier coatings *John Hutchinson* (35)	**Fluid dynamics of animal swimming and flying** ▶	How insects fly *Jane Wang* (74)
1			**Mechatronics** ▶	Trajectory planning for linearly-actuated elastic robots using flatness based control theory *Mathias Bachmayer* (62)
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	Mon 11:20 Lecture	Mon 11:40 Lecture	Mon 12:00 Lecture	Mon 12:20 Lecture
A	*Lecture continues*	Vortices in quantum fluids *Natalia Berloff* (70)	*Lecture continues*	Quantum fluid questions suggested by phenomena in classical fluids *Karim Shariff* (71)
B	*Lecture continues*	Colloidal chemo-mechanics of engineering materials: clays, earth and cement *Henri Van Damme* (65)	*Lecture continues*	Colloids and microfluidics *David Weitz* (66)
C	*Lecture continues*	Bridged and cohesive crack models for fracture in composite material systems *Roberta Massabò* (46)	*Lecture continues*	Modelling strain localization by cohesive/overlapping zones in tension/compression... *Alberto Carpinteri* (47)
D	*Lecture continues*	Modelling multi-scale damage evolution in composite materials *Brian Cox* (53)	*Lecture continues*	Instabilities across the scales *Hans Muhlhaus* (54)
E	*Lecture continues*	Fish swimming dynamics: knowns and unknowns *Daniel Weihs* (74)	*Lecture continues*	Understanding swimming at low Reynolds numbers: successes and challenges *Lisa Fauci* (75)
1	Design and control of a hybrid micromanipulator with piezoelectic actuators and vision feedback system *Daniel Prusak* (62)	Classical mechanics and electromagnetism: a covariant view *Markus Schöberl* (62)	Friction discs: torsional slip control and radial dynamics *Alexander Fidlin* (63)	Adaptive LQ controller for position control of machine tool axis *Petr Strakos* (63)
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	Mon 12:40 Lecture			Mon 14:00 Lecture	Mon 14:20 Lecture
A	*Lecture continues*	Lunch :: Mon 13:00–14:00	**Waves** ▶	A practical forecast model for atmospheric internal waves produced by a mountain *James Rottman* (191)	Internal solitary waves of very large amplitude subject to shear-instability *John Grue* (191)
B	*Lecture continues*		**Flow instability and transition** ▶	The inviscid Rayleigh–Taylor instability *Larry Forbes* (130)	A new instability in thermal boundary layers *Jianjun Tao* (130)
C	*Lecture continues*		**Convection** ▶	Boundary layer structure in highly turbulent Rayleigh–Bénard convection *Ronald du Puits* (102)	Scaling of the local convective heat flux in turbulent Rayleigh–Bénard convection *Penger Tong* (102)
D	*Lecture continues*		**Experimental methods in fluid mechanics** ▶	Delta surface hot-wires as a means of measuring wall shear stresses at arbitrary flow directions *Christoph Dobriloff* (122)	Lorentz force velocimetry: theory and practice *André Thess* (122)
E	*Lecture continues*		**Experimental methods in solid mechanics** ▶	The effect of vibration, amplitude of vibration, roughness, and speed on the friction coefficient of metals *Jamil Abdo* (235)	Recent developments and applications of the ISSR technique *Keyu Li* (235)
1	New active mounting of machine tool feed drives *Jiri Sveda* (63)		**Computational solid mechanics** ▶	Multiscale FE simulation for crack propagation in heterogeneous media with microstructures *Seyoung Im* (201)	3D gradient elastic crack analysis by the BEM *Dimitri Beskos* (201)
2			**Biomechanics** ▶	Real-time simulation of non-linear tissues by model reduction techniques *Francisco Chinesta* (330)	Thin films of transversely isotropic fluid: applications to collagen gels *Edward Green* (330)
3			**Multibody and vehicle dynamics** ▶	A fast iterative solution of the wheel-rail contact *Ingo Kaiser* (284)	Comparison of fast algorithm and FEM results for wheel-rail contact simulation *Alexander Olshevsky* (284)
4			**Contact and friction mechanics** ▶	A class of dynamic contact interaction problems in viscoelasticity *Marius Cocou* (210)	Effect of adhesion in sliding contact of rough bodies *Irina Goryacheva* (210)
5			**Geophysical and environmental fluid dynamics** ▶	Equilibrium states of quasi-geostrophic vortices *Takeshi Miyazaki* (148)	Investigating the formation of wind-formed dune fields based on discrete dynamics *Xiaojing Zheng* (148)
6			**Plasticity and viscoplasticity** ▶	A finite strain theory of gradient crystal plasticity *Mitsutoshi Kuroda* (299)	A canonical numerical formulation for wrinkling in elastoplastic membranes under large deformations *Joern Mosler* (299)
8			**Impact and wave propagation** ▶	Dynamic strain localization and fragmentation *Krishnaswamy Ravi-Chandar* (258)	A substructure technique for impact-induced transient wave of discontinuous flexible system with wave... *Yunian Shen* (258)
10			**Mechanics of composites** ▶	Buckling of imperfect cylindrical composite shells using Reissner–Mindlin–von Karman shell facet model *Petri Kere* (272)	Effective properties of nonlinear power law elastic periodic composites *Vincent Monchiet* (272)

	Mon 14:40 Lecture	Mon 15:00 Lecture	Mon 15:20 Lecture	Mon 15:40 Lecture
A	Nonlinear wave excitation of capillary waves in the presence of hydrocarbon films *Horst Punzmann* (192)	Open channel flow past a curved sluice gate *Ben Binder* (192)	Wave-coherent tangential stress due to smaller scale breaking *William Peirson* (192)	Surface gravity waves in Lagrangian description of motion *Didier Clamond* (192)
B	Wake structures behind a rolling sphere on a wall *Bronwyn Stewart* (130)	Computation of convective instability in complex geometry flows *Hugh Blackburn* (131)	Effect of surface roughness on the laminar–turbulent transition in channel flow *Jerzy Floryan* (131)	Secondary instability of variable-density jets *Jean-Marc Chomaz* (131)
C	Stability of buoyancy and surface-tension driven convection in a horizontal double-diffusive layer *Chuan Chen* (102)	On thermal plumes in convective turbulence *Ke-Qing Xia* (103)	Heat and mass transfer features in magneto-polarized colloids *Alexandra Bozhko* (103)	Effect of the magnetic field on the flow inside droplet on a substrate *Masayuki Kaneda* (103)
D	Measurement of unsteady surface forces by means of pressure sensitive copolymer coatings *Jan Domhardt* (122)	Global Doppler imaging with near-resonant interferometry *Andrin Landolt* (123)	Control of the depth of correlation in micro-PIV using a novel post-processing method *Chuong Nguyen* (123)	Pressure and temperature measurements of supersonic microjet impingement *Chihyung Huang* (123)
E	Measurements of discontinuous displacement fields by extended 3D image correlation by X-ray tomography *Francois Hild* (235)	In-situ investigation of nano-scale plasticity in FCC and BCC crystals by homog. deformation of nano-pillars *Julia Greer* (236)	Characterization of the stress–strain relationships of ductile films using sharp indentation *Yyongli Huang* (236)	Evaluation of whole-field thin-film stress and strain by the biharmonic function *Wei-Chung Wang* (236)
1	Nonconforming BETI/FETI method for time domain elastodynamics *Martin Schanz* (201)	Two-field and two-scale computational homogenization for coupled thermo-mechanical problems *Marc Geers* (202)	A generalized cosserat point element for isotropic nonlinear elastic materials including irregular 3D brick... *Miles Rubin* (202)	Model verification in dynamics through strict upper error bounds *Pierre Ladeveze* (202)
2	Partitioned FEM/FVM coupling for cardiac fluid-structure interaction with a macroscopic... *Sebastian Krittian* (330)	Constitutive modeling of the stress–strain behavior of F-actin filament networks *Jeffrey Palmer* (331)	Investigations of invariant based constitutive laws for modelling myocardial mechanics *Holger Schmid* (331)	Resonance in the cochlea with wave packet pseudomodes *Dominik Obrist* (331)
3	On the contact detection for contact analysis in multibody systems *Paulo Flores* (284)	Oscillation reduction of cranes by hoisting manipulation *Edwin Kreuzer* (285)	Planetary rover mobility performance on soft and uneven terrain *Bernd Schäfer* (285)	Smoothing friction phenomena in railway dynamics *Werner Schiehlen* (285)
4	Contact analysis with non-linear elasticity and combined cone/spherical indenter *Pauli Pedersen* (210)	Influence of contact geometry on hardness values *Weimin Chen* (211)	Dynamic effects of a sliding tread block on concrete surfaces *Patrick Moldenhauer* (211)	Adhesion of elastic spheres: finite element modeling, Derjaguin approximation *Harish Radhakrishnan* (211)
5	The effect of thermal diffusion on the stability of strongly tilted mantle plume tails *Ross Kerr* (148)	Experimental study on propagation velocities of water surface ripples and turbulence in open-channels *Hitoshi Miyamoto* (149)	Effects of upstream disturbances in a model of headland wakes *Melanie O'Byrne* (149)	Mixing in baroclinic exchange flows and its dependence on topography *Ross Griffiths* (149)
6	Thermodynamic coarse-graining of dislocation mechanics and the size-dep. continuum plasticity *Sinisa Mesarovic* (299)	Progress in homogenization of elasto-plastic and elasto-viscoplastic inclusion-reinforced composites *Issam Doghri* (300)	The effect of void shape on size-dependent void growth *Christian Niordson* (300)	Characterization of strain rate dependent deformation behavior of carbon-black filled rubber *Yoshihiro Tomita* (300)
8	Dynamic test of the main aircraft landing gear with failure *Wieslaw Krason* (258)	Modeling mechanical response and failure of ice submitted to high velocity impacts *Yann Chuzel-Marmot* (259)	Bloch–Floquet flexural waves and localised defect modes in thin elastic plate structures *Natasha Movchan* (259)	Modelling stress wave propagation under biaxial loading using SPH *Rajarshi Das* (259)
10	A coupled analytical model for hydrostatic response of 1-3 piezocomposites *Nimal Rajapakse* (272)	3D elastodynamics of an interface crack *Igor Guz* (273)	Analyses of a metallic rod bridging a unbonded interface *Brian Legarth* (273)	Damage evolution during thermo-oxidation of polymeric matrix composites *Kishore Pochiraju* (273)

			Mon 16:25 Lecture	Mon 16:45 Lecture	Mon 17:05 Lecture
A	**Coffee break :: Mon 16:00–16:25 Hall K**	**Waves** ▶	Nonlinear three-dimensional interfacial flows *Emilian Parau* (193)	Inertial estimates of surface wave dissipation due to breaking *Kendall Melville* (193)	Spatial and temporal evolution of wave groups: experiments versus simulations *Lev Shemer* (193)
B		**Acoustics** ▶	Silent embedded boundaries for combustion noise simulation *Wolfgang Schröder* (327)	Effect of non-axisymmetric flow disturbances on the sound generation in the hole-tone feedback cycle *Mikael Langthjem* (327)	Models for acoustic propagation through turbofan exhaust flows: lined ducts *Nigel Peake* (327)
C		**Drops, bubbles and multiphase flows** ▶	Turbulent sediment suspension and particle-fluid coupling in oscillating flows under ripple-bed conditions *Ken Kiger* (108)	Shock fluidization of solids and liquids *Vladimir Mitkin* (108)	Particle spin in rotating and shearing flows *Johanna Bluemink* (108)
D		**Stirring and mixing** ▶	Stretching and mixing of chemically reactive chaotic flows *Paulo Arratia* (179)	Chaotic mixing in a helix-like pipe with periodic variations in curvature and torsion *Mitsuaki Funakoshi* (179)	Topological chaos in flows on surfaces of arbitrary genus *Matthew Finn* (179)
E		**Experimental methods in solid mechanics** ▶	Mechanical characterization of materials by micro-indentation and AFM scanning *Gabriella Bolzon* (237)	Determination energy dissipation for aluminium deformed dynamically at modified Taylor impact test *Leopold Kruszka* (237)	3D volumetric DIC of X-ray microtomographic images to study localized deformation in a stiff clayey rock *Jacques Desrues* (237)
1		**Geophysics and geomechanics** ▶	Modelling high pressure shear using breakage mechanics *Itai Einav* (252)	Mechanical characteristics of seismic waves estimated from earthquake-induced structural failures *Koji Uenishi* (252)	Mechanisms of dynamic friction at slip rates appropriate for earthquake faulting *Yuri Fialko* (252)
2		**Biomechanics** ▶	Biomechanical models of epidermal wound closure in embryos *Alexander Sadovsky* (332)	Longterm prediction of bone remodelling effect around implant *Vaclav Klika* (332)	Mechanics of memory and learning *Taher Saif* (332)
3		**Education in mechanics** ▶	Some outstanding events and persons in the history of mechanics *Olga Kryuchkova* (367)	Practical study for vehicle dynamics *Yoshio Kano* (367)	Design and use of supplementary software for an undergraduate program in eng. science/mechanics *Glenn Kraige* (367)
4		**Nanostructures and MEMS** ▶	Mechanics and physics of dislocation nucleation in nanostructured metals *Ting Zhu* (293)	Thermo-elastic size-dependent properties of nano-composites with imperfect interfaces *Bhushan Karihaloo* (293)	Plectoneme formation in fluctuating DNA *Prashant Purohit* (293)
5		**Structural optimization** ▶	Topological design of isotropic composites *Vivien Challis* (312)	Efficient optimization-based form finding of cable nets in uniform fluid flow *Michael Winther* (312)	Topology optimisation for micropolar elastic solids *Yutaka Arimitsu* (312)
6		**Plasticity and viscoplasticity** ▶	Incremental variational principles with application to homogenization of non-linear dissipative composites *Pierre Suquet* (301)	On the link between discretization and higher order homogenization of elastic-plastic composites *Kenneth Runesson* (301)	Mesoscopic modeling of the relaxation of intrinsic stress in thin films by grain boundary diffusion and... *Erik van der Giessen* (301)
8		**Fluid-structure interactions** ▶	Flow around a tethered neutrally-buoyant sphere *Kerry Hourigan* (348)	Energy transfer in fluid–structure interactions *Tatyana Krasnopolskaya* (348)	Collective flutter of a parallel plate assembly *Lionel Schouveiler* (348)
10		**Mechanics of composites** ▶	Modeling of the degradation of laminates under impact: some key points *Olivier Allix* (274)	Delamination of compressed thin layers at corners *Johan Clausen* (274)	Multiple curved micro-beams model for in-plane mechanical properties of stitched composite laminates *Junqian Zhang* (274)

	Mon 17:25 Lecture		Tue 08:30 Lecture	
A	Short-crested gravity waves of large amplitude in deep water *Makoto Okamura* (194)	**Fluids and Solids Sectional Lectures** ▶	Biomechanical aspects in human reproduction *David Elad* (44)	**Classical and quantum vortex rings** ▶
B	Sound generation in flows with steady heat communication *Nader Karimi* (328)	**Fluid Mechanics Sectional Lectures** ▶	Nonlinear transient growth on a vortex column *Fazle Hussain* (39)	**Mechanics of colloidal systems** ▶
C	Motion of bubbles in aqueous surfactant solutions *Yoichiro Matsumoto* (109)	**Fluids and Solids Sectional Lectures** ▶	From dry granular flows to submarine avalanches *Olivier Pouliquen* (44)	**Cohesive zone models of fracture and failure** ▶
D	Tailoring chaotic mixing within a translating droplet by oscillatory rotation *Rodolphe Chabreyrie* (180)	**Solid Mechanics Sectional Lectures** ▶	Self-healing materials systems: where mechanics meets chemistry *Nancy Sottos* (41)	**Fluid dynamics of animal swimming and flying** ▶
E	A new method for characterizing the surface periodic structure of photonic crystal and its application *Huimin Xie* (238)			
1	3D modeling of dynamic and quasi-static fault slip: interaction of dynamic rupture with a stronger patch... *Nadia Lapusta* (253)			
2	Multiscale analysis of the human aortic valve *Mohammad Mofrad* (333)			
3	Photoelasticity as a teaching aid for the finite element method *Schalk Kok* (368)			
4	On the ratio between surface tension and the bulk modulus of materials *Graham Weir* (294)			
5	On optimization of involute gear teeth *Niels Pedersen* (313)			
6	Simulation of deformation and fracture of metal/ceramic interfaces *Siegfried Schmauder* (302)			
8	Flow behind a cylinder forced by a combination of oscillatory translational and rotational motions *David Jacono* (349)			
10	Characterization of interface adhesion of dissimilar elastic-plastic materials by a pressurized blister test model *Yichun Zhou* (274)			

	Tue 09:15 Lecture	Tue 09:35 Lecture	**Coffee break :: Tue 09:55–10:40 Hall K**		Tue 10:40 Lecture
A	Vortex rings and their use *Carlo Barenghi* (71)	*Lecture continues*		**Classical and quantum vortex rings** ▶	Relative equilibria of point vortices *Hassan Aref* (71)
B	The hydrodynamics of self-propelled suspensions *Sriram Ramaswamy* (66)	*Lecture continues*		**Mechanics of colloidal systems** ▶	Liquid crystalline elastomers and magnetic gels: similarities and differences in their physical properties *Harald Pleiner* (66)
C	Cohesive-zone modelling of adhesive joints *Michael Thouless* (47)	*Lecture continues*		**Cohesive zone models of fracture and failure** ▶	Fracture in confined thin films: a discrete dislocation study *Audrey Chng* (47)
D	The effect of body cross-sectional shape on glide force production in ‘flying’ snakes *John Socha* (75)	Fluid-dynamic effects of both rigid and free boundaries on the swimming of singly flagellated bacteria *Tomonobu Goto* (75)		**Multi-component materials, modelling on different scales** ▶	Chemically driven inelastic deformation in materials with non-ideal sources and sinks for vacancies *Franz Fischer* (54)
E				**Fluid dynamics of animal swimming and flying** ▶	Instability of uniform suspensions of swimming micro-organisms *Timothy Pedley* (76)
1				**Fracture and crack mechanics** ▶	A predictive model for chipping wear of hard coatings *Leon Keer* (241)
2				**Biomechanics** ▶	The intervertebral disc as a saturated porous material *Nils Karajan* (333)
3				**Multibody and vehicle dynamics** ▶	Measurements and simulations or rail vehicle dynamics with respect to overturning risk *Dirk Thomas* (286)
4				**Elasticity** ▶	Nonlinear bulk strain waves in layered elastic waveguides with delamination: theory and experiments *Karima Khusnutdinova* (223)
5				**Flow instability and transition** ▶	Convective and absolute instability of two miscible fluid core-annular flow *Dominique Salin* (132)
6				**Geophysical and environmental fluid dynamics** ▶	The viscous phase of horizontal gravity currents: how is the time evolution of the front selected? *Yannick Hallez* (150)
8				**Mechanics of phase transitions** ▶	Virtual melting mechanism of crystal-amorphous and crystal-crystal phase transformations & plastic relaxation *Valery Levitas* (280)
10				**Microgravity fluid mechanics** ▶	Boiling heat transfer in microgravity *Jian-Fu Zhao* (171)

	Tue 11:00 Lecture	Tue 11:20 Lecture	Tue 11:40 Lecture	Tue 12:00 Lecture
A	Alignment of strain and vorticity in vortex interactions *Robert Kerr* (71)	Motion of vortex rings with and without magnetic field *Yasuhide Fukumoto* (72)	Curvature instability of a vortex ring and a helical vortex tube *Yuji Hattori* (72)	Vortex ring chain due to the periodic motion of a sphere *Viatcheslav Meleshko* (72)
B	On the origin of the remarkable stability of aqueous foams *Dominique Langevin* (67)	Self-assembly of particles for 2D lattices with adaptable spacing *Nadine Aubry* (67)	Microfluidic colloidal island self-assembly and erasure induced by surface acoustic waves: I. experiments *Leslie Yeo* (67)	Cross-stream migration of colloidal particles in confined flows *Peter Daivis* (68)
C	Length-scale dependency of crack tip fields under mode I loading *Lars Mikkelsen* (48)	Direct extraction of rate-dependent traction-separations laws for polyurea/steel interfaces *Kenneth Liechti* (48)	Micromechanics of elasto-damaging cohesive materials *Bernhard Pichler* (48)	A cohesive model coupling friction and adhesion for interfaces and fractures and applications *Michel Raous* (49)
D	An analysis of textile reinforced concrete structures on the micro, meso and macro scale *Bernd Zastrau* (54)	Multiscale computing of CNTS fracture based on quasicontinuum/density functional theory hybridization *Jong Park* (55)	Micromechanics of deformation of persulfonated polytetrafluoroethylene proton exchange membranes *Meredith Silberstein* (55)	Constitutive description of plastic strain induced phenomena at cryogenic temperatures *Blazej Skoczen* (55)
E	Scaling of wake energy and propulsive efficiency of two representative jellyfish species: Aurelia & Mastigias *Kakani Katija* (76)	Optimal flexibility of a flapping appendage at high Reynolds number *Silas Alben* (76)	Fluid dynamic simulation of human sperm accumulation near to surfaces *John Blake* (77)	Linked bodies swimming through a free surface *Jules Kajtar* (77)
1	Structural-kinetic approach in dynamics of continuum: fracture, spalling, cavitation, electrical breakdown *Arseny Kashtanov* (241)	Dynamic fatigue behavior of cracked piezoelectric ceramics in three-point bending under electromechanical load *Yasuhide Shindo* (242)	An extended Gurson model accounting for strain localization within thin planar layers *Jean-Baptiste Leblond* (242)	Condition for crack deviation in an anisotropic solid and its dependence on a crack model *Efim Shifrin* (242)
2	Mechanics of traumatic brain injury at multiple length scales *Johannes van Dommelen* (333)	Microvascular-based multifunctional structural materials *Scott White* (334)	Computational simulation of red blood cell motion in microvessels and bifurcations *Timothy Secomb* (334)	Influence of endothelium monolayer unevenness on leukocyte deformation and migration *Pushpendra Singh* (334)
3	Environmental and track perturbations on multiple pantograph interaction with catenaries in high-speed trains *Jorge Ambrósio* (286)	Dynamic characteristics of pseudo-rigid bodies *Li-Sheng Wang* (286)	Analytical and experimental analysis of a parallel leaf spring guidance *Jacob Meijaard* (287)	Numerical and experimental analysis of an automotive clutch disc *Samir Sfarni* (287)
4	Plane waves in nonlinear anisotropic elasticity *Wlodzimierz Domanski* (223)	Propagation of magnetoelastic waves in a vortex field in a superconducting layer *Bogdan Maruszewski* (224)	Reciprocity relations in Newtonian and Eshelbian mechanics *Reinhold Kienzler* (224)	Numerical analysis of stress singularity in three-dimensional problems of elasticity theory *Valeriy Matveyenko* (224)
5	Transition to turbulence in a pipe *Tom Mullin* (132)	Transitional plane Couette flow: an alternative to the low-dimensional dynamical system approach *Paul Manneville* (132)	The strato-rotational instability with and without boundaries: application to Keplerian flows *Stéphane Le Dizès* (133)	Global low-frequency oscillations in a separated boundary layer *Francois Gallaire* (133)
6	Inertia-gravity wave generation: a geometric-optics approach *Jacques Vanneste* (150)	Forward energy cascade of geostrophic turbulence via near-boundary instabilities *William Dewar* (150)	Transcritical small disturbance theory for flow over topography *Ted Johnson* (151)	Solution of some vortical free boundary problems arising in ocean flows *Nicholas McDonald* (151)
8	Multi-phase-field recrystallization simulation based on deformation microstructure *Tomohiro Takaki* (280)	Nucleation and growth of stress-induced martensitic fine layered structures in shape memory alloys... *Yongzhong Huo* (280)	Elastoplastic phase-field simulation of cubic-tetragonal martensitic transformation in polycrystals *Akinori Yamanaka* (281)	Electrical induced crack propagation and domain switching in ferroelectric single crystal *Daining Fang* (281)
10	Vibration-induced Rayleigh instability in supercritical fluids under microgravity conditions *Daniel Beysens* (171)	Capillary channel flows *Michael Dreyer* (171)	Experiments on aqueous foams in microgravity to study poroelastic effects in soft wet cellular materials *Arnaud Saint-Jalmes* (172)	The capillary flow experiments aboard ISS: weakly 3D interior corner flows *Mark Weislogel* (172)

	Tue 12:20 Lecture			Tue 14:00 Seminar	Tue 14:05 Seminar
A	The effect of a uniform cross-flow on the circulation of vortex rings *Eyad Hassan* (73)	Lunch :: Tue 12:40–14:00	**Boundary layers** ▶	Characterising hairpin vortex packets in a low Reynolds number turbulent boundary layer *Chong Wong* (80)	Wind-tunnel studies on global unsteadiness of laminar separation bubbles *Alexander Dovgal* (80)
B	Hydrodynamic crystals: collective dynamics of regular arrays of spherical particles in a parallel-wall channel *Eligiusz Wajnryb* (68)		**Computational solid mechanics** ▶	Natural boundary element method for mixed boundary problem of circular plate *Zhengzhu Dong* (203)	Numerical analysis on the mechanics characteristic of spot-welding-flake-strain-sensor *Yongjun Xu* (203)
C	General method for micromechanical based derivation of separation laws *Ingo Scheider* (49)		**Computational fluid dynamics** ▶	ALE-multigrid fictitious boundary method for Navier–Stokes equations with free moving solid boundaries *Decheng Wan* (97)	Numerical simulation of ice accretion on airfoils *Yihua Cao* (97)
D	Stresses in topologically interlocking structures: two scale approach *Arcady Dyskin* (56)		**Elasticity** ▶	The Flamant and Carothers type problems for cusped prismatic shells *George Jaiani* (225)	Geometry, dynamics and fractals *Marcelo Barros* (225)
E	The upstream wake of swimming and flying animals and its correlation with propulsive efficiency *Jifeng Peng* (77)		**Drops, bubbles and multiphase flows** ▶	Bubble resonance frequencies as a function of pressure *Richard Manasseh* (109)	Rheological properties of suspensions of noncolloidal particles in yield stress fluids *Xavier Chateau* (109)
1	Analysis of notches and cracks in laminated plates by means of scaled boundary finite elements *Jochen Hebel* (243)		**Fracture and crack mechanics** ▶	Incubation time based fracture mechanics *Yuri Petrov* (243)	The problem of co-linear twin cracks in elastic wave field *Bing-zheng Gai* (243)
2	Recent progress in the theoretical and computational modelling of flow in 3D collapsible tubes *Matthias Heil* (335)		**Experimental methods in solid mechanics** ▶	The research of measuring polymerization shrinkage of composite resins with ESPI *Guobiao Yang* (238)	Development of an automated load and measurement device *Mohsen Javadi* (238)
3	Dynamic analysis of rail vehicles and investigation of potential derailment caused by wheelflats *Wen-Fang Wu* (287)		**Impact and wave propagation** ▶	Emergence of soliton trains in microstructured materials *Andrus Salupere* (260)	Propagation of surface SH waves on a half space coated with a nonlinear thin layer *Ali Demirci* (260)
4	Materials with Poisson's ratio near −1: properties and possible realisations *Elena Pasternak* (225)		**Microgravity fluid mechanics** ▶	Behaviour of drops and bubbles in non-uniform pulsational flows *Tatyana Lyubimova* (173)	Viscosity measurement via drop coalescence: a space station experiment *Basil Antar* (173)
5	Instability of steady and pulsatile flow in stenotic geometries *Martin Griffith* (133)		**Turbulence** ▶	A new look into re-effect on turbulent round jets *Jamie Mi* (183)	Drag reduction of a deforming film covered with polysaccharide in turbulent water flow *Yoshimichi Hagiwara* (183)
6	The behaviour of dilute particle suspensions in waning flows *Robert Dorrell* (151)		**Structural vibrations** ▶	Phenomenological mapping method and mathematical analogy of hubrid system dynamics *Katica Hedrih* (317)	Elastoplastic and geometrically non-linear vibrations of beams by the p-version finite element method *Pedro Ribeiro* (317)
8	Micromagnetic theory of ferromagnetic shape memory alloys *Jiangyu Li* (281)		**Combustion and flames** ▶	A mechanistic model for the catalytic growth of carbon nanotubes and their combustion synthesis *Ishwar Puri* (87)	Characteristics of flow behaviors behind rifled nozzles *Kuo-Ching San* (87)
10	Reduced gravity testing and research capabilities at Queensland University of Technology's new 2.0s drop tower *Ted Steinberg* (172)		**Contact and friction mechanics** ▶	Two smoothing methods in frictional beam-to-beam contact: a numerical comparison *Przemyslaw Litewka* (212)	Micro/nanoscale friction and its dependence on contact area *Sriram Sundararajan* (212)

	Tue 14:10 Seminar	Tue 14:15 Seminar	Tue 14:20 Seminar	Tue 14:25 Seminar
A	Experimental investigation of coherent structure dynamics in the outer layer of a turbulent boundary layer *Gerrit Elsinga* (80)	Bursting phenomena of boundary layer induced by 2D vortex patch *Henryk Kudela* (81)	Mixed convection boundary layer flow from a vertical stretching sheet in a thermally stratified micropolar fluid *Roslinda Nazar* (81)	A comparison of internal and external turbulent boundary layers *Nicholas Hutchins* (81)
B	Exact solutions of frame structures *Haitao Ma* (203)	Gl mechanical and electromagnetic coupled field modeling and inversion *Ganquan Xie* (204)	A new rotation vector update for path-independent and strain-objective geometrically exact beam *Susanta Ghosh* (204)	Frequency dependent wave propagation in functionally graded materials *Laurent Aebi* (204)
C	RANS prediction of free surface effects on the drag coefficient of an underwater hull form *Jagadeesh Putta* (97)	Operator-splitting scheme for a Bingham fluid in a cavity flow *Zhenjiang You* (98)	Adaptive finite element simulation of self-patterning phase decomposition *Roy Stogner* (98)	Laminar displacement of viscoplastic fluids in eccentric annuli: numerical simulation and experimental validation*Dzuy Nguyen*(98)
D	Axisymmetric solution for a tetragonal medium *Marc Dahan* (225)	Influence functions and integral formulae for spherical thermoelastic bodies *Seremet Victor* (226)	Multi-field modelling of short wavelength deformations for Cosserat solids *Andrey Miroshnichenko* (226)	Elastic fields in quantum dot structures with arbitrary shapes and interface effects *Jianxiang Wang* (226)
E	Air cushioning and bubble entrapment in three dimensional droplet impact *Peter Hicks* (110)	Interaction of gaseous bubbles under the action of radiation modified Bjerknes force *Yury Stepanyants* (110)	Towards efficient modeling of cavitation erosion potential in pumps *Patrik Zima* (110)	Surface profiles of collapsing cavities of splash drops *Jong-Leng Liow* (111)
1	Multiscale energy momentum tensor and its application to fracture *Shaofan Li* (243)	Thermal shock solution of a functionally graded material plate with arbitrary thermo-mechanical properties... *Li-cheng Guo* (244)	Stress fields near mode II interface crack tip of two dissimilar orthotropic composite materials *Li Junlin* (244)	Energy analysis of the brittle fracture of solid with cracks *Igor Dunaev* (244)
2	The optoelectronic method for measurement of small dynamic displacements *Michael Osipov* (239)	Acoustic emission detection for damage evaluation of thermal barrier coatings under cyclic heating *Li Yang* (239)	A lattice unit model to evaluate interfacial residual stress in ferroelectric thin film *Xuejun Zheng* (239)	A novel magnetostrictive acoustic transducer for longitudinal guided wave inspection of steel strands *Zenghua Liu* (240)
3	Guided elastodynamic waves in functionally graded cylindrical structures *Jacqueline Vollmann* (260)	High velocity penetration into ground media *Igor Simonov* (261)	Dispersive behavior of waves in pre-stressed imperfectly bonded compressible elastic layered composites *Anil Wijeyewickrema* (261)	Thermoacoustic effect in thin plates with residual stresses *Ching-Chung Yin* (261)
4	Planar migration of two drops in a thermal gradient *Ren Sun* (173)	Numerical simulations of drop thermocapillary migration with variable viscosities *Zhaohua Yin* (174)	Effect of eccentric rotation on the equilibrium shapes and stability of liquid bridges in a lateral gravity field *Ana Laverón* (174)	Stability analysis of thermocapillary convections in liquid bridges with Pr=100 under microgravity *Qi-Sheng Chen* (174)
5	The growth rate in Rayleigh–Taylor instabilities by overturning experiment in tank *Xi Li* (183)	Statistical theory of inhomogeneous turbulence based on cross-independence closure hypothesis *Tomomasa Tatsumi* (184)	The influence of turbulence on a columnar vortex with axial flow *Naoya Takahashi* (184)	Numerical and experimental study of stability of isothermal and hot round jet *Stanislaw Drobniak* (184)
6	Nonlinear parametric vibration of axially accelerating beams *Li-Qun Chen* (318)	Vibrations of a beam with a sliding mass *Hassan Nahvi* (318)	Gap waves propagating in layered piezoelectric material structures with initial stress *Jianke Du* (318)	Vibration and buckling behaviour of soft core sandwich plate using improved higher order zigzag theory *Bhrigu Singh* (318)
8	Thermal structures and combustion efficiency of non-premixed reacting rifled nozzles *Shun-Chang Yen* (87)	**Complex and smart fluids** ▶	Coarse-graining hydrodynamic interactions in isolated polymer molecules in solution *Prabhakar Ranganathan* (91)	Turbulence structures in turbulent boundary layer flows of cationic and non-ionic surfactant solutions *Motoyuki Itoh* (91)
10	A new contact width model for an automatic polishing process *Wei-Ling Kuo* (212)	Connected models of friction of rolling, sliding and whirling in problems of solids dynamics *Alexey Kireenkov* (213)	Analytic solution of spherical indentation problem for a half-space with functionally graded elastic coating *Sergey Aizikovich* (213)	On plane contact problems under partial reverse slip condition *Haradanahalli Murthy* (213)

	Tue 14:30 Seminar	Tue 14:35 Seminar	Tue 14:40 Seminar	Tue 14:45 Seminar
A	Series solution of non-similarity boundary-layer flows of non-Newtonian fluids *Shijun Liao* (82)	**Flow control** ▶	Flow control by turbulence state modifications in the near-wall region *Bettina Frohnapfel* (127)	Optimization of the dynamic properties of compliant coating *Inwon Lee* (127)
B	Multi-scale investigation of crystal plasticity *Zhuo Zhuang* (204)	Deformation simulation under constant volume condition using phase field crystal method *Tomoyuki Hirouchi* (205)	Free vibration analysis of unsymmetric 6-noded element under mesh distortion *Senthilkumar Vaiyapuri* (205)	Numerical solution of fractional derivative equations in mechanics: advances and problems *Wen Chen* (205)
C	DES simulations of the unsteady flow field around the Stratospheric Observatory for Infrared Astronomy *Sven Schmid* (98)	Consistency in symmetry for numerical schemes *Marx Chhay* (99)	Effect of inverted aerofoil geometry on aerodynamic performance in ground effect *Jonathan Vogt* (99)	Shear viscosity along the freezing line of Weeks–Chandler–Andersen fluid *Alauddin Ahmed* (99)
D	Size effect on probability of quasibrittle failure and lifetime: from atomistic to structural scale *Sze-Dai Pang* (227)	GILD mechanical field modeling *Feng Xie* (227)	Intrinsic field tensors for strongly orthotropic continua *David Kellermann* (227)	Stress analysis of curved elastic bar and elastic wedge under bending load *Vyacheslav Lyakh* (228)
E	Dependence of saturated vapor pressure and surface tension coefficient on radius for an argon nano-droplet *Shigeo Fujikawa* (111)	Oscillation frequency and deformation of levitated droplets *Tadashi Watanabe* (111)	An investigation of droplets impinging on liquid film *Jiahong Guo* (112)	The zipping wetting dynamics at the breakdown of superhydrophobicity *Peichun Tsai* (112)
1	Strain-energy criteria and fracture of plastic bodies in a neighborhood of strain concentrators *Anastasia Bukhanko* (245)	Support to rock excavations provided by adhesive liners *Herven Abelman* (245)	Research on mixed mode and mode II crack growth in orthotropic composites by caustics method *Zheng Li* (245)	3D interface crack in fully coupled electromagnetothermoelastic multiphase anisotropic composites *BoJing Zhu* (246)
2	**Multi-component materials, modelling on different scales** ▶	Nonlinear dynamic response and self-sensing of functionally graded piezoelectric transducers *Fumio Narita* (56)	Evolution of the bonding mechanism of ZnO under isotropic compression: a first-principles study *Jinbin Wang* (56)	Response of solids under electrical, magnetic, and mechanical loads *Su Hao* (57)
3	An experimental study of plate wave diffraction tomography *Andrew Rohde* (262)	Energy dissipation study for drop test of landing gear *Jerzy Malachowski* (262)	Three-dimensional reflection and refraction of seismic waves in highly anisotropic media *Amares Chattopadhyay* (262)	Far-field solution of SH-wave by circular lining and linear crack *Hongliang Li* (262)
4	Effect of microgravity on interface shape: simulation using smoothed particle hydrodynamics *Arup Das* (175)	Mass transfer in supercritical carbon dioxide *Rainer Benning* (175)	**Magnetohydrodynamics** ▶	Influence of magnetic and electrical fields on a thin layer of electrically conducting liquid *Hamid Abderrahmane* (163)
5	CICLoPE: a new high Reynolds number pipe flow facility for detailed turbulence measurements *Jean-Daniel Rüedi* (185)	Direct numerical simulation of turbulence in a fully-developed channel flow with permeable boundaries *Satoshi Yokojima* (185)	Concentration of active nonlinear energy transfer in rolling-up vortices *Keisuke Araki* (185)	Investigation of Smagorinsky model in large-eddy simulation of periodic turbulent shear flows *Yihong Fang* (186)
6	Vibration localization in disordered periodically stiffened double-leaf panels *Gui-Lan Yu* (319)	Magnetic damping of resonant rotor-bearing vibrations *Wlodzimierz Kurnik* (319)	Difference resonances in a controlled van der Pol–Duffing oscillator *Jinchen Ji* (319)	Chaotic vibrations of a post-buckled cantilevered beam constrained by a stretched string at the top end *Ken-ichi Nagai* (320)
8	**Convection** ▶	Direct numerical simulation of forced convection heat transfer from two staggered circular cylinders *Sirod Sirisup* (104)	Two-dimensional thermal convection in a parallelogram-shaped cavity with tilted sidewalls *Yoshinari Fukazawa* (104)	Temperature derivatives and thermal dissipation in turbulent Rayleigh–Bénard convection *Joerg Schumacher* (104)
10	**Damage mechanics and fatigue** ▶	High rate loading and unexpected phenomena *Nikita Morozov* (218)	Life prediction based on crack growth analyses in microstructures modeled by Voronoi-polygons under... *Toshihiko Hoshide* (218)	Anisotropic damage participation in online hybrid testing application *Abdulfatah Souid* (218)

	Tue 14:50 Seminar	Tue 14:55 Seminar	Tue 15:00 Seminar	Tue 15:05 Seminar
A	**Low-Reynolds-number flow** ▶	On the effects of atmospheric pressure, air concentration in a fluid, and the surface roughness on... *Alexander Prokunin* (157)	A fast boundary element method for Stokes flow *Kian-Meng Lim* (157)	Arbitrary oscillatory Stokes flow past a porous sphere: Faxen's laws *Raja Sekhar* (157)
B	On the nonuniqueness of BIEM/BEM using SVD *Jeng-Tzong Chen* (206)	**Geophysics and geomechanics** ▶	Earthquake source mapping using strong motion array data *Narayana Iyengar* (253)	Using fundamental solutions of mechanics of deformable rigid body in geomechanical problems *Andrew Krupoderov* (253)
C	Inverse radiative problem with natural convection phenomenon *Yun Hong* (100)	**Waves** ▶	Combined approach to modelling of spatially nonlinear waves in shallow layers of viscous liquids *Georgy Khabakhpashev* (194)	Analyses on the flapping frequency of turbulent jets in a narrow channel *Jianhong Sun* (194)
D	Mechanics of nonlinear acoustoelasticity in fluid-saturated porous rocks *Jing Ba* (228)	Analytical mechanics of bars, plates and shells on asymmetrical theory of elasticity *Samvel Sargsyan* (228)		
E	Simulation of elastic objects in viscous fluid flows *Howard Hu* (112)	**Turbulence** ▶	Intensive turbulent convection *Ilias Sibgatullin* (186)	Turbulent flow past a rectangular cylinder confined in channel *Dong-Hyeog Yoon* (186)
1	**Viscoelasticity and creep** ▶	Bases and advances of the synthetic theory of irreversible deformation *Endre Ruszinko* (326)	An advanced rapid three-dimensional modeling technology for asphalt concrete *Xinhua Yang* (326)	
2	Implicit constitutive modeling based on the energy principle *Hou Man* (57)	**Mechatronics** ▶	Representation of hysteresis in discrete electro-magneto-mechanical systems *Andreas Mueller* (64)	Analysis of with lower limb orthosis at sit to stand state *Dein Shaw* (64)
3	Calculation collisions by using inverse method *Janis Viba* (263)			
4	Importance of new magnetic field analysis for interface phenomena of ferromagnetic fluid *Yo Mizuta* (163)	**Mechanics of colloidal systems** ▶	Memories in paste of flow and vibration: their visualizations as crack patterns *Akio Nakahara* (68)	Microfluidic colloidal island self-assembly and erasure induced by surface acoustic waves: II. dynamic analysis *James Friend* (69)
5	**Compressible flow** ▶	Schlieren visualisation of rocket nozzle exhaust flow *Yvette McPhail* (94)	The aerodynamics of aerofoils and wings in transonic ground effect *Graham Doig* (94)	**Acoustics** ▶
6	Proposals for visualising the evolution of approximate analytical solutions in engineering dynamics *Matthew Cartmell* (320)	Nonlinear transient vibration of an axially moving string with an attached traveling oscillator under wind... *Yuefang Wang* (320)	Stochastic data-based representation of uncertain complex non-linear systems *Sami Masri* (321)	PDF solution to nonlinear oscillators excited by Gaussian and Poisson white noises *Hai Zhu* (321)
8	Unsteady natural convection in a differentially heated partitioned cavity *Feng Xu* (105)	Bifurcations in convection of incompressible fluid in a rotated square cylinder *Sergey Suslov* (105)	**Porous media** ▶	Simulation of carbonate matrix acidizing *Bulgakova Guzel* (363)
10	An analytical model for frictional load transfer in a clearance fit bolted joint *Ligieja Paletti* (219)			

	Tue 15:10 Seminar	Poster viewing and coffee :: Tue 15:15–16:00 Hall K		Tue 16:00 Lecture	Tue 16:20 Lecture
A			**Waves** ▶	Nonlinear surface water waves over a random bottom *Walter Craig* (195)	Impact of a heavy vertical jet on a horizontal wall *Paul Christodoulides* (195)
B			**Elasticity** ▶	A multiscale projection method for fracturing solids in three dimensions *Stefan Loehnert* (229)	Variational treatment of crack problems in plane micropolar elasticity *Stanislav Potapenko* (229)
C	Dynamic wave impact simulation using an innovative particle-cluster scheme *André Baeten* (195)		**Cohesive zone models of fracture and failure** ▶	Simulation of delamination growth under high-cycle fatigue using cohezive-zone models *Albert Turon* (49)	Cohesive model and experimental analysis of PMMA at high rate *Rafael Estevez* (50)
D			**Multi-component materials, modelling on different scales** ▶	Crystal microstructure design of piezoelectric materials by multiscale finite element analysis *Yasutomo Uetsuji* (57)	Constitutive model of discontinuous plastic flow at cryogenic temperatures *Jan Bielski* (58)
E			**Flow in thin films** ▶	Thin film flows over real surfaces *Yeaw Lee* (143)	Interfacial turbulence in falling liquid films *Serafim Kalliadasis* (143)
1			**Fracture and crack mechanics** ▶	Fracture simulation of concrete using fractal approach and lattice model: validation by AE study *Remalli Sagar* (246)	Multiple cracking of an embedded concretion *Dominique Leguillon* (246)
2	Deformation and fracture behavior of ceramic-polymer ferroelectric nanocomposite film under uniaxial tension *Fei Fang* (64)		**Biomechanics** ▶	An actin-driven model for neuronal growth cone motility and axon guidance *Zhu Weiping* (335)	Collective behavior of sarcomere ensembles: evolution of non-uniformities and insights on muscle function *Kaushik Bhattacharya* (335)
3			**Boundary layers** ▶	Bifurcation phenomena in incompressible laminar ramp flow *Alfred Kluwick* (82)	Boundary-layer breakdown in a rotating, fluid-filled torus *Richard Clarke* (82)
4	The effect of temperature on strain wave superstructures on two-dimensional colloidal crystals with confinement… *David Chui* (69)		**Damage mechanics and fatigue** ▶	Phenomenological approach to the description of deformation and fracture of damaged solids *Evgeny Lomakin* (219)	Damage evolution in explosion of a particulate composite circular cylinder *Romesh Batra* (219)
5	AGILD WMT ray-tracing interactive tomography *Jianhua Li* (328)		**Structural vibrations** ▶	Normal vibration modes of a slender beam on elastic foundation with unilateral contact *Carlos Mazzilli* (321)	Forced response of waveguides from finite element analysis *Brian Mace* (322)
6			**Geophysical and environmental fluid dynamics** ▶	The large-scale effect of mesoscale ocean–atmosphere coupling *Andrew Hogg* (152)	Adjustment processes in horizontal convection *Graham Hughes* (152)
8			**Geophysics and geomechanics** ▶	Fluid-driven fracture growth along an existing natural fracture *Xi Zhang* (254)	Predicting behavior in granular materials via multiscale computations *Jose Andrade* (254)
10			**Impact and wave propagation** ▶	Asymptotic analysis of linear wave propagation in and free vibrations of elastic helical springs *Sergey Sorokin* (263)	Modelling of explosion damage tolerance in advanced space structures subject to hypervelocity… *Andrew Litchfield* (263)

	Tue 16:40 Lecture	Tue 17:00 Lecture	Tue 17:20 Lecture	
A	Nonlinear surface waves in a square liquid tank under obliquely horizontal excitation *Takashi Ikeda* (196)	Effect of surface stress on the propagation of solitary water waves *Paul Hammerton* (196)	Giant solitons on deep water and freak waves *Vladimir Zakharov* (196)	
B	Two-dimensional thermoelasticity problems for a rectangle *Yuriy Tokovyy* (229)	On the mechanical analysis of plates composed of functionally graded material *Holm Altenbach* (229)	Time dependent mechanical response of the cell cytoskeleton *Robert McMeeking* (230)	
C	Element-free Galerkin modelling of cohesive crack propagation in composite laminates *Brian Falzon* (50)	Measurement and modeling of interfacial behaviors between thin films and substrates using peel test *Yueguang Wei* (50)	A mixed-mode constitutive damage model for multi-scale fracture analysis of composite structures *Anders Hansen* (51)	
D	Transition between models in multiscale simulations: continuum and granular models *Jagan Padbidri* (58)	Optimization and identification of multi-component materials in modelling on different scales *Tadeusz Burczynski* (58)	Propagating modes of nano-scale periodic layers of solid-fluid composites *Chien-Cheng Chang* (59)	**Rodney Hill Prize Lecture** ▶
E	A general free surface rule for Stokes flow of fluid films over obstacles *Markus Scholle* (143)	Experimental and theoretical modelling of ice sheet–shelf grounding lines *Grae Worster* (144)	Structure of a pure-vapor–liquid contact line on a heated substrate: truncated adsorbed microfilms and... *Alexey Rednikov* (144)	**Batchelor Prize Lecture** ▶
1	Spontaneous crack propagation in functionally graded materials *Dhirendra Kubair* (247)	Crack bridging model for nanocomposites *Mikhail Perelmuter* (247)	Non-linear crack growth in short steel fibre reinforced concrete: modeling and experimental verification *Andrejs Krasnikovs* (247)	
2	Russian doll poroelasticity; a model for fluid transport in tissues *Stephen Cowin* (336)	Three-dimensional computational modeling and simulation of cell motion on adhesive surfaces in shear flow *Prosenjit Bagchi* (336)	Non-Newtonian fluid flow simulation in a progressively enlarged aneurysm model *Panagiotis Neofytou* (336)	
3	On unsteady boundary-layer separation in supersonic flow *Anatoly Ruban* (83)	Transient growth induced by surface roughness in a Blasius boundary layer *Philippe Lavoie* (83)	The turbulent shear stress in zero pressure gradient boundary layers *Peter Monkewitz* (83)	
4	Analytical correlations between the fatigue properties of engineering materials *Marco Paggi* (220)	Evaluation of damage development in piezoelectric ceramics under repeated mechanical loading *Mamoru Mizuno* (220)	Modelling progressive dynamic damage in advanced re–entry space transportation composite/hybrid structures *Javid Bayandor* (220)	
5	Inverse dynamic approach of statistical health monitoring of structure from limited noisy data *Debasish Bandyopadhyay* (322)	Nonlinear vibrations of an annular hyperelastic membrane *Paulo Gonçalves* (322)	Damage identification in multilayer composite structures using Lamb stress waves *Wieslaw Ostachowicz* (323)	
6	Three-dimensionality in electromagnetically driven shallow flows *GertJan van Heijst* (152)	Physics of the mesoscale atmospheric turbulence: laboratory experiments *Michael Shats* (152)	Absence of small-scale fluctuations of high-Prandtl number scalars in stratified turbulence *Hideshi Hanazaki* (153)	
8	Laboratory experiments and theoretical studies of rupture modes and supershear transition *Xiao Lu* (254)	Mathematical theory of plasticity for frictional materials *Kristian Krabbenhoft* (255)	Earthquake nucleation on geometrically complex faults *Guanshui Xu* (255)	
10	Plasticity-damage versus anisotropic damage for impact on concrete structures *Marion Chambart* (264)	The dynamics of pizza tossing *Kuang-Chen Liu* (264)	On Hayes waves *Philippe Boulanger* (264)	

	Wed 08:30 Lecture		Wed 09:25 Lecture		
A		**Solid Mechanics Sectional Lectures** ▶	Characterization of heterogeneous materials by multi-scale simulations *Peter Wriggers* (41)	Coffee break :: Wed 10:10–10:40 Hall K	**Waves** ▶
B		**Fluid Mechanics Sectional Lectures** ▶	Bubbles in micro- and nano-fluidics *Detlef Lohse* (39)		**Compressible flow** ▶
C		**Fluid Mechanics Sectional Lectures** ▶	Capillary constructions *David Quéré* (39)		**Low-Reynolds-number flow** ▶
D	Nonconvex plasticity and deformation microstructures *Michael Ortiz* (38)	**Solid Mechanics Sectional Lectures** ▶	Failure of rocks in the laboratory and the Earth *John Rudnicki* (42)		**Multi-component materials, modelling on different scales** ▶
E	Interfaces: in fluid mechanics and across disciplines *Howard Stone* (37)				**Porous media** ▶
1					**Fracture and crack mechanics** ▶
2					**Biomechanics** ▶
3					**Boundary layers** ▶
4					**Chaos and pattern formation in fluid and solid mechanics** ▶
5					**Plasticity and viscoplasticity** ▶
6					**Combustion and flames** ▶
8					**Geophysics and geomechanics** ▶
10					**Mechanics of composites** ▶

	Wed 10:40 Lecture	Wed 11:00 Lecture	Wed 11:20 Lecture	Wed 11:40 Lecture
A	Three-dimensional gravity capillary free surface flows *Jean-Marc Vanden-Broeck* (197)	Adaptive direct numerical simulation of steep water waves *Stéphane Popinet* (197)	On the inclusion of arbitrary topography and bathymetry in the nonlinear shallow-water equations *Raphael Poncet* (197)	Space-time measurements of breaking wave kinematics and void fraction in the surf zone *Olivier Kimmoun* (198)
B	The von Neumann paradox for strong shock reflection *Susumu Kobayashi* (94)	Experimental investigation of tripping between regular and Mach reflection in the dual-solution domain *Hans Hornung* (95)	Shock regularisation in dense gases by viscous inviscid interaction *Georg Meyer* (95)	Shock wave reflection from curved surfaces *Beric Skews* (95)
C	Eddy reversals in three dimensions *Christopher Hills* (158)	Viscous flow past two spherical cavities in porous media: application to drug delivery system *Osamu Sano* (158)	Three flow regimes of a viscous jet falling onto a moving surface *Andriy Hlod* (158)	The irreversible effect of cavitation in near-contact region *Alan Graham* (159)
D	A multiscale model for the sintering of air-plasma sprayed thermal barrier coatings *Alan Cocks* (59)	Multi-scale modeling of stress-induced microstructures in shape memory alloys *Henryk Petryk* (59)	Parametric study of strain hardening behaviour of glassy polymers using molecular simulations *Sumit Basu* (60)	Ductile damage evolution in two-phase metallic materials applied at cryogenic temperatures. *Halina Egner* (60)
E	The tip of a fluid-driven fracture in a permeable elastic medium *Yevhen Kovalyshen* (363)	Swelling phenomena in chemically active hydrated materials *Wolfgang Ehlers* (363)	Stress measures in partially saturated porous media mechanics *Bernhard Schrefler* (364)	Simulation, modelling and measurement of dispersive flow in bead packs *Howard Davis* (364)
1	A computational method for three dimensional finite deformation fracture *Dana Mueller-Hoeppe* (248)	Computational approach for fatigue crack propagation in ship structures under random clustered loading *Yoichi Sumi* (248)	Dominant mechanism for crack propagation in nonplanar interface *Abhijit Dasgupta* (248)	Simulation of crack propagation in functionally graded materials *Li Ma* (249)
2	Separatrices and basins of stability from time series data *Shane Ross* (337)	Computational design of novel stem cell based therapies for myocardial infarction *Ellen Kuhl* (337)	Material characterization of biological membranes by inverse analysis *Martin Kroon* (337)	Cosserat theoretical modeling of single actin filament as a twisted elastic filament *Hidetaka Yamaoka* (338)
3	Boundary-layer separation and vortex generation in a suddenly blocked pipe *Jim Denier* (84)	On the relationship between large- and small-scale motions in turbulent boundary layers *Romain Mathis* (84)	A high Reynolds number turbulent boundary layer with regular roughness *Jason Monty* (84)	Non-universality of overlap region in turbulent pipe and channel flows *Hassan Nagib* (85)
4	Misleading dye visualization near a 3D stagnation point with applications to the vortex breakdown bubble *Morten Brons* (344)	Chaos thresholds in vibro-impact systems with heavy elastic elements *Tomasz Kapitaniak* (344)	Experimental chaos in impact oscillator *Ekaterina Pavlovskaia* (345)	Chaos control by application of magnetorheological damping *Jerzy Warminski* (345)
5	Computational challenges in finite plasticity from a mathematical view point *Carsten Carstensen* (302)	Grain size effect and intrinsic material length of a polycrystal *Ke-Shi Zhang* (302)	Hardening and softening in micro and nanoplasticity *Carl Dahlberg* (302)	Discrete and continuum dislocations and plastic hardening of crystals *Pilar Ariza* (303)
6	OH-PLIF visualisation of radical farming supersonic combustion flows *Russell Boyce* (88)	The response of inverted flames to equivalence ratio modulations *Sebastien Candel* (88)	The effects of turbulence, hot spots, and stochasticity on the deflagration-to–detonation transition *Elaine Oran* (88)	Detonation structure for chain-branching kinetics: an analysis in the small initiation rate Limit *Luc Bauwens* (89)
8	Spectral element simulations of dynamic rupture along non planar faults *Jean-Pierre Vilotte* (255)	A multiscale modelling of damage and time dependent plastic behavior of cohesive rocks: formulation and... *Jian-Fu Shao* (256)	Multi-phase coupled elasto-viscoplastic analysis of unsaturated soil slope during seepage flow *Fusao Oka* (256)	Thermomechanics of faults *Emmanuil Veveakis* (256)
10	Transverse crack behavior in satin woven carbon fiber reinforced/epoxy composite laminates at cryogenic... *Shinya Watanabe* (275)	Micromechanics-based nonlocal modeling of elastic matrices containing aligned spheroidal inclusions *Ilaria Monetto* (275)	The effect of interfaces on the plastic behavior of periodic composites *Martin Idiart* (275)	Free edge effects of thermoplastic composite laminates *Min Shen* (276)

	Wed 12:00 Lecture	Wed 12:20 Lecture	Wed 12:40 Lecture	Excursions :: Wed 13:00–17:00	
A	Numerical study of breaking waves of different intensities *Alessandro Iafrati* (198)	The frequency and wavevector spectra of gravity wave turbulence in the laboratory flume *Sergei Lukaschuk* (198)	Airflow separation above wind waves *Fabrice Veron* (199)		**Solid Mechanics Sectional Lectures** ▶
B	Low frequency unsteadiness in shock induced separated flows *Sébastien Piponniau* (96)	Experiments on supersonic cavity flows with passive control *Sudhir Gai* (96)	European research on unsteady effects of shock wave induced separation: UFAST project *Jean-Paul Dussauge* (96)		**Fluid Mechanics Sectional Lectures** ▶
C	Microcapsule flow in small pores: method for determining elastic properties of the membrane *Dominique Barthès-Biesel* (159)	Weak inertial effects associated with oscillating pressure in a 3D channel *Guibert Romain* (159)	Stokeslet induced flows in the vicinity of a hybrid compound droplet *Devanayagam Palaniappan* (160)		**Fluids and Solids Sectional Lectures** ▶
D	Multiscale models for multi-component structural energetic materials *Sathya Hanagud* (60)	Inverse modelling to find fibre hygroexpansion coefficient from experimental wood-fibre composites swelling *Karin Almgren* (61)	Constitutive model of plastic strain induced FCC–BCC phase transformation at cryogenic temperatures *Adam Wroblewski* (61)		**Fluids and Solids Sectional Lectures** ▶
E	Wave propagation in partially-saturated rocks: theoretical and numerical investigation *Holger Steeb* (364)	Effect of vibrations on stability of displacement front *Dmitriy Lyubimov* (364)	A micromechanical modeling of poroplastic behaviour of saturated microcracked media *Djimédo Kondo* (365)		
1	Determination of the effective material properties of a linear elastic material with a randomly distrib... *George Mejak* (249)	Damage tolerance of a sandwich panel with square honeycomb core *Ignacio Alonso* (249)	Assessment on the structural integrity based on 3D crack growth simulations *Wilhelm Weber* (250)		
2	Ionised media and fractures: application to cartilaginous tissues and oil industry *Jacques Huyghe* (338)	An anisotropic micro-sphere-based model for arterial tissue *Andreas Menzel* (338)	Modeling skin wrinkling for reconstructive surgery: the effects of natural tension *Luigi Gambarotta* (339)		
3	Sub-optimal control of unsteady boundary-layer separation in a channel with suction *Kevin Cassel* (85)	Towards simulations of high-Reynolds number turbulent boundary layers *Philipp Schlatter* (85)	Pipe flow turbulence in the presence of roughness *Alexander Smits* (86)		
4	Nonsmooth mechanics: challenges and unsolved problems *John Hogan* (345)	Coexistence of synchronous states in chaotically driven mechanical oscillators *Andrzej Stefanski* (345)	Exploring extensive chaos in Rayleigh–Bénard convection using fractal and Karhunen-Loève dimensions *Andrew Duggleby* (346)		
5	Ductile damage development in friction stir welded aluminum joints *Kim Nielsen* (303)	Bauschinger effect in freestanding thin films modeled by discrete dislocation plasticity *Lucia Nicola* (303)	Viscoplasticity of ice single crystals loaded in torsion: experiments and discrete dislocation dynamics simul. *Marc Fivel* (304)		
6	Temporally resolved pseudo-3D measurements of turbulent flame interactions using orthogonal-plane... *Adam Steinberg* (89)	Behaviour of stability limits of non-premixed jet flames in a co-flowing air stream *Teresa Leung* (89)	Numerical optimization of shock to detonation transition by using shaped tubes *Ilya Semenov* (90)		
8	Propagation of shear waves in an elastic layer with void pores *Prakash Pal* (257)	Non-Euclidean model of the zonal disintegration of rocks around an underground working *Mikhail Guzev* (257)			
10	Continuum analysis for a unidirectional composite with a penny shaped crack *Michael Ryvkin* (276)	On modelling reinforced composites exhibiting stochastic uncertainties on volume fraction... *Johann Guilleminot* (276)	Transient response of active constrained-layer damped FGM beams *Donatus Oguamanam* (277)		

	Thu 08:30 Lecture		Thu 09:15 Lecture	Thu 09:35 Lecture
A	Plasto-mechanics of large deformation under impact loading *Narinder Gupta* (42)	**Waves** ▶	On the self-similarity of short-wavelength incipient spilling breakers *James Diorio* (199)	Measurements of growth rates of wind-generated water waves *Dan Liberzon* (199)
B	Indian Ocean Dipole and its possible link with climate modes *Toshio Yamagata* (40)	**Education in mechanics** ▶	Teaching the modelling of structures *Juha Paavola* (368)	Class participation experiments in mechanics: two-force members *Richard McNitt* (368)
C	Cellular matter: interfacial mechanics and geometry *Sascha Hilgenfeldt* (45)	**Structural vibrations** ▶	Guided waves damage detection in beams utilising Bayesian artificial neural network model class selection *Ching Ng* (323)	Bifurcation patterns of a whirling transported string *Gert van der Heijden* (323)
D	Material instabilities in elastic and plastic solids *Davide Bigoni* (45)	**Stability of structures** ▶	Structural and failure performance of load-carrying lattice structures *Hans Obrecht* (306)	Buckling of single-crystal silicon nanolines under indentation *Rui Huang* (306)
E		**Granular materials and flows** ▶	Ripple and undulation on vertically vibrated granular layers: dependence on material properties *Ataka Takei* (356)	Highly nonlinear solitary waves in periodic granular media *Chiara Daraio* (356)
1		**Flow in thin films** ▶	Are outside corners more difficult to coat than inside ones? *Mathieu Sellier* (144)	Sliding drops of generalized Newtonian liquid *Leonard Schwartz* (145)
2		**Biomechanics** ▶	Liquid crystal model of vesicles under electromechanical fields *Xi-Qiao Feng* (339)	The hysteretic large strain behavior of mussel byssal threads *Brian Greviskes* (339)
3		**Damage mechanics and fatigue** ▶	Residual strength based lifetime prediction of composite materials subjected to spectrum loading *Scott Case* (221)	Modeling of hydrogen embrittlement of metals in wet H_2S containing environments *Vladimir Astafiev* (221)
4		**Elasticity** ▶	The role of fiberwise constraints in the mechanics of linearly elastic shells *Paolo Podio-Guidugli* (230)	Finite-amplitude Love waves in a pre-stressed neo-Hookean material *Elizabete Ferreira* (230)
5		**Turbulence** ▶	Scale dependence of coarse-grained velocity gradient in turbulence *Eberhard Bodenschatz* (187)	Multiscale geometrical analysis of vorticity and dissipation in homogeneous turbulence *Dale Pullin* (187)
6		**Low-Reynolds-number flow** ▶	Periodic orbits of Stokesian dynamics *Maria Ekiel-Jezewska* (160)	Large-scale simulations of emulsion flow through a granular material *Alexander Zinchenko* (160)
8		**Magnetohydrodynamics** ▶	Equilibrium and stability in relaxed magnetohydrodynamics of toroidal plasmas *Robert Dewar* (163)	Magnetic field reversals in nature, experiments and simulations *Andre Giesecke* (164)
10		**Complex and smart fluids** ▶	Yielding behaviour without an explicit yield stress for soft materials *Roger Tanner* (92)	Jet breakup of polymeric fluids *Oliver Harlen* (92)

	Thu 09:55 Lecture	Thu 10:15 Lecture			Thu 11:00 Lecture
A	Drag on a ship and Michell's integral *Ernest Tuck* (200)	Visco potential free-surface flows *Denys Dutykh* (200)	**Coffee break :: Thu 10:35–11:00 Hall K**	**Flow instability and transition** ▶	Transition control in swept-wing boundary layers *William Saric* (134)
B	The use of simplified strain gradient elasticity in structural analysis *Antonios Giannakopoulos* (368)	Promoting education of applied mechanics by mechanics contest *Nelson Chen* (369)		**Convection** ▶	Viscous boundary layer measurement in turbulent thermal convection *Chao Sun* (105)
C	Experimental unfolding and reduced order model in the complex dynamics of a sagged cable *Giuseppe Rega* (324)	Subcritical flutter in the problems of acoustics of friction *Oleg Kirillov* (324)		**Drops, bubbles and multiphase flows** ▶	A theoretical growth model for dynamic slugs in gas/liquid horizontal pipes *Usama Kadri* (113)
D	Mechanically-triggered transformations of pattern and phononic band gaps in periodic elastomeric structures *Katia Bertoldi* (306)	Lüders bands induced localization and propagation of curvature in steel tubes under pure bending *Stelios Kyriakides* (307)		**Computational fluid dynamics** ▶	A material interface transition algorithm for multiphase flow simulation *Marianne Francois* (100)
E	Crushing of granular media by a discrete numerical modeling *Mohamed Guessasma* (356)	A constitutive model for unsaturated granular materials *Pierre-Yves Hicher* (357)		**Foams** ▶	Viscoelastic properties of open cell Kelvin foams *Heinz Pettermann* (370)
1	Stability of a thin radially moving liquid sheet in the presence of acoustic excitation *Mahesh Tirumkudulu* (145)	Hydrodynamics of reactive thin films *Antonio Pereira* (145)		**Control of structures** ▶	Design of resonant vibration absorbers with filtered feedback *Steen Krenk* (215)
2	Red blood cell deformation behavior in a high-shear flow *Shigeo Wada* (340)	Peristalsis and hydrodynamic instabilities *Jerome Hoepffner* (340)		**Computational solid mechanics** ▶	Vibration of thick plates under in-plane loading using finite strip-elements *Joe Petrolito* (206)
3	Mean stress effect and bi-axial fatigue of structures from two scale damage model *Gregory Barbier* (221)	FE simulation and life prediction of thermal fatigue failure of the continuous casting tundish cover *Xia Zhou* (222)		**Fracture and crack mechanics** ▶	Exact solution of a penny-shaped crack in piezoelectric materials with electric saturation at the crack tip *Weiqiu Chen* (250)
4	Effect of cubic elasticity on the distribution of stress in polycrystals *Maxime Sauzay* (230)	On variational formulations for nonlocal elasticity *Francesco de Sciarra* (231)		**Impact and wave propagation** ▶	A new concept of dynamic biaxial plastic crushing of metallic thin-walled tubes *Akrum Abdul-Latif* (265)
5	Turbulence suppression by self-generated and imposed large-scale flows *Hua Xia* (187)	Deterministic wall turbulence and its applications *Yury Kachanov* (187)		**Turbulence** ▶	A bound for turbulent pair dispersion *Michael Borgas* (188)
6	Low-Reynolds streaming in a cavity: an illustration of inviscid flow *Josue Sznitman* (161)	Expanding volumes of channelized viscous gravity currents *Daisuke Takagi* (161)		**Solidification and crystal growth** ▶	Heterogenous nucleation and successive microstructure evolution during solidification *Heike Emmerich* (176)
8	Investigation of interface oscillations in liquid metals using magnetic field tomography *Christian Resagk* (164)	Dissipation bounds for dynamos *Thierry Alboussière* (164)		**Granular materials and flows** ▶	Influence of particle shape in the statistical mechanics of classical gases *Fernando Alonso-Marroquin* (357)
10	Drop impact of yield-stress fluids *Li-Hua Luu* (92)	The dynamics of visco-elastic bridges in drop coalescence *Aleksey Rozhkov* (93)		**Microfluidics** ▶	Semi-automated manipulation of crystals using acoustic fields and microfluidics in micromachined devices *Stefano Oberti* (166)

	Thu 11:20 Lecture	Thu 11:40 Lecture	Thu 12:00 Lecture	Thu 12:20 Lecture
A	Symmetry breaking in two-dimensional, diverging-channel flow *Philip Haines* (134)	Experiments on the elliptic instability in vortex pairs with axial core flow *Thomas Leweke* (134)	Interactions between wave motions and a spanwise array of streamwise streaks *Jonathan Watmuff* (135)	Sensitivity and forcing response in separated boundary-layer flow *Jean-Christophe Robinet* (135)
B	Unsteady natural convection in a reservoir model subject to periodic heating and cooling at the water surface *Tomasz Bednarz* (106)	An experimental study of transient natural convection in a side-cooled cavity *Obai Younis* (106)	Modes of the convection in triaxial ellipsoid *Aleksander Kozlov* (106)	Unsteady jet impingement: a systematic study of its heat transfer performance *Heinz Herwig* (106)
C	The effect of shear on the size distribution in concentrated vesicle suspensions *Gary Leal* (113)	The impulsive generation of drops at a fluid-fluid interface *William Phillips* (113)	Microbubble pinch-off in flow-focusing devices *Wim van Hoeve* (114)	Direct numerical simulation of interface turbulence interaction *Jean-Luc Estivalezes* (114)
D	Molecular simulation of shearing dense hyperbranched polymer fluids *Tu Le* (100)	Simulation of atomizing jets with OCT-tree adaptive mesh refinement *Stephane Zaleski* (101)	A dynamic wall model constrained by external Reynolds stress *Krishnan Mahesh* (101)	Modelling the wall roughness for RANS and LES using the discrete element method *Franco Magagnato* (101)
E	Structure and rheology of wet foams *Andrew Kraynik* (370)	On the crushing of metallic open-cell foams *Wen-Yea Jang* (370)	Representative volume element size and analysis of the deformation mechanisms of open-cell foams *Anthony Burteau* (371)	Multi-scale modelling of fracture in metal foams *Patrick Onck* (371)
1	Controlled onset of low-velocity collisions in vibro-impacting systems with friction *Harry Dankowicz* (215)	A variational approach to 3D rod motion modeling and optimization *Georgy Kostin* (215)	Mobile systems controlled by internal moving masses *Felix Chernousko* (216)	Optimum control of thermal stress in a piezo-composite disk *Fumihiro Ashida* (216)
2	Micropolar cohesive zone model for delamination failure in microsystem interconnects *Yan Zhang* (206)	Numerical simulation of glass fragmentation under impact using a coupled damage/decohesion model... *Luming Shen* (207)	Neural networks for meshless and pufem approaches *Luca Facchini* (207)	Deformability of flexibly jointed structure with negative Poisson's ratio *Hiro Tanaka* (207)
3	Pre-existing fluid driven fracture in permeable rock *David Mason* (250)	Unidirectional 'DCB' and 'ENF' specimens: a comparative study between finite elements and higher... *Raghu Prasad* (250)	Microstructural simulation on the brittle versus ductile transition of nanocrystalline metals *Wei Yang* (251)	Mixed-mode fracture in viscoelastic orthotropic material *Rostand Pitti* (251)
4	Surface waves in phononic crystals with large acoustic mismatch: band structure analysys by wavelet method *Yue-Sheng Wang* (265)	Measurements of Lamb wave band gaps and guided waves in air/silicon phononic plates and channels *Tsung-Tsong Wu* (265)	Experimental study on negative effective mass in a 1D mass-spring system *Gengkai Hu* (266)	Use of magnesium for lightweight and crashworthy S-frame *Parisa Tehrani* (266)
5	Experimental measurement of acceleration correlations in turbulent flows of dilute polymer solutions *Haitao Xu* (188)	Physical mechanism of the energy cascade in homogeneous turbulence *Susumu Goto* (188)	On local cascade structures of turbulence *Zhen-Su She* (189)	A study of subgrid models in lattice Boltzmann-based large eddy simulation *Yu-Hong Dong* (189)
6	Asymptotic results for a Stefan problem with surface tension *Scott McCue* (176)	Steady-state solidification of aqueous solutions in a new directional solidification facility *Herbert Huppert* (176)	Experimental compaction in a crystallizing mushy zone *Renaud Deguen* (177)	Modelling the growth and motion of a free dendrite under terrestrial conditions *Minh Do-Quang* (177)
8	Computer modelling of doming phenomenon in flow of granular–cohesive material *Zdzislaw Wieckowski* (357)	Dense granular materials are Cosserat continua *Prabhu Nott* (358)	Scaling the final deposits of dry cohesive granular columns after collapse and quasi-static fall *Catherine Meriaux* (358)	Thermomicromechanical continuum theory for granular materials *Antoinette Tordesillas* (358)
10	Microflow induced by Opercularia Assymetrica: optical experimental investigations *Bogumila Zima-Kulisiewicz* (166)	Computational study of a novel valve mechanism for synthetic jet actuator *Victoria Timchenko* (166)	Numerical studies of nonlinear kinetics in induced-charge electro-osmosis *Henrik Bruus* (167)	Non-local transport in nanofluids: k-space and real-space viscosity kernels *Ruslan Puscasu* (167)

	Thu 12:40 Lecture			Thu 14:00 Seminar	Thu 14:05 Seminar
A	Optimal perturbation in a channel flow: adjoint-based and Riccati-based control comparison *Patricia Cathalifaud* (135)	**Lunch :: Thu 13:00–14:00**	**Nanostructures and MEMS** ▶	Estimation of load-capacity of multi-layered porous nanofilters *Adam Kovacs* (294)	Anisotropic polling and piezoelectric behaviors in rhombohedral ferroelectric single crystals *Ai-Kah Soh* (294)
11			**Biomechanics (Room 11)** ▶	Elementary mechanics of muscular exercise *Antonio DiCarlo* (340)	Simulation of migrating cell growth under limited nutrient supply based on a cellular automata model *Chih-Ang Chung* (341)
C			**Elasticity** ▶	The definition of the displacement function by the elements of Cauchy's tensor *Turatbek Duishenaliev* (231)	New model for piezoelectric medium with initial porosity and analysis of ultrasonic piezoelectric devices *Andrey Nasedkin* (231)
D			**Fluid dynamics of animal swimming and flying** ▶	Analysis of ciliary gliding in freshwater planarians *Takeshi Sugimoto* (78)	Experimental comparison of a steady and unsteady self-propelled swimmer *Lydia Trevino* (78)
E	Pressure-driven and free-rise foam flow *Lisa Mondy* (371)		**Drops, bubbles and multiphase flows** ▶	Study on the occurrence of the liquid jet and the bubble breakup in a convergent divergent channel flow *Kazuya Shimizu* (114)	Binary droplet collision at high impact *Kuo-Long Pan* (115)
1	Equilibrium stabilization via position and delayed position feedback *Haiyan Hu* (216)		**Impact and wave propagation** ▶	The role of nonequilibrium in Hugoniot of a porous material *Anatoly Resnyansky* (266)	Normal wave propagation in a rectangular elastic waveguide *Anastasiya Bondarenko* (266)
2	Nonlinear coupled FE–simulation of thermoelectro-mechanical processes in thin-walled structure *Ruediger Schmidt* (208)		**Stability of structures** ▶	Thermal post-buckling behavior of FG panels in supersonic airflows *Ji-Hwan Kim* (307)	Multi-bifurcation analysis for the multi-folding structures *Ichiro Ario* (307)
3			**Flow instability and transition** ▶	Biglobal stability analysis of an unsteady separated flow with wall curvature *Julio Soria* (136)	On investigation of sinusoidal and varicose instabilities of streaks in boundary layers *Victor Kozlov* (136)
4			**Material instabilities** ▶	Effects of energy-providing components in 2D discrete structures *Yun-Che Wang* (269)	Material stability conditions for a class of inhomogeneous anisotropic media *Carlos Daros* (269)
5			**Mechanics of composites** ▶	Micromechanism of deformation in EMC laminates *Zhengdao Wang* (277)	Thermo-mechanical constitutive laws for particle-reinforced composites including... *Yasser Shabana* (277)
6			**Geophysical and environmental fluid dynamics** ▶	Some investigations into near surface wind and saltation intensity in mining area *Ning Huang* (153)	PIV measurements in the immediate wake of a cactus-shaped cylinder *Ghanem Oweis* (153)
8			**Multibody and vehicle dynamics** ▶	Development of a dynamic analysis solver using an object-oriented programming method *Jiwon Yoon* (287)	Dynamics model and algorithm of floating raft with elastic limiters *Jianming Wen* (288)
10			**Fluid-structure interactions** ▶	Hydroelastic analysis of multiple articulated floating elastic plates *Trilochan Sahoo* (349)	The effect of surface condition on the vortex-induced vibration response of cylindrical offshore structures *Brad Stappenbelt* (349)

	Thu 14:10 Seminar	Thu 14:15 Seminar	Thu 14:20 Seminar	Thu 14:25 Seminar
A	Nanomechanical deflection of DNA chips induced by hybridization exothermic effect *Neng-Hui Zhang* (295)	Characterization of nanoimprinting polymers with laser ultrasonics *Juerg Bryner* (295)	Elastic properties of nanostructures with the charged surfaces *Linli Zhu* (295)	Influence of dislocation distribution density on interface relaxation stress in heteroepitaxial thin films... *Igor Dobovsek* (296)
11	Micro and macro shape deviations of the contact areas of the hip joint endoprosthesis *Vladimir Fuis* (341)	Structure overload and structural anisotropy in human vertebral trabecular bone *Nicola Fazzalari* (341)	Study on deformation of vesicle membrane based on evolution of topological defects *Akihiro Nakatani* (342)	Investigation of the surface interactions of the implant-bone *Romuald Bedzinski* (342)
C	Continuum dislocation theory and size effect *Khanh Le* (232)	Notes on stresses in chains *Marcelo Epstein* (232)	Green's function for plane anisotropic elastic bimaterials with imperfect interface *Leszek Sudak* (232)	**Structural optimization** ▶
D	A force element theory with applications to insect flight *Chin-Chou Chu* (78)	A biomimetic figure-of-eight flapping induced by flexible wings *Lung-Jieh Yang* (79)	Robustness of an insect's hovering: a transition of flapping free-flight *Makoto Iima* (79)	The fluid mechanical basis of jellyfish feeding and the effects of prey size and escape forces *Madeline Miller* (79)
E	Effects of interfacial waves on turbulent mass transfer in a open channel flow *Yosuke Hasegawa* (115)	Micromechanics of gas filled microballoons *Paulo Fernandes* (115)	Inclined drop impact onto a curved surface *Ilia Roisman* (116)	Foam films of pure liquids *Satomi Onishi* (116)
1	Repeated impact between two flexible rods *Ali Tian* (267)	Effects of micro-structures on the in-plane dynamic crushing of lattice materials *Ying Liu* (267)	Study on the structure health monitoring based on AE and SMI technology *Ying Luo* (267)	Studies on the dynamic behavior of aluminum alloy foams *Hongwei Ma* (268)
2	Wrinkling of thin rectangular plates under longitudinal tension *Barrie Fraser* (308)	The computation of sensitivity analysis of stability problems of steel plane frames *Zdenek Kala* (308)	A new result in linear stability *Jean Lerbert* (308)	Plastic buckling and post-buckling of rectangular plates, experiments and their simulation by FE... *Suresh Shrivastava* (309)
3	An experimental and numerical study of the Faraday instability with miscible liquids *Sakir Amiroudine* (136)	Relaxation approach for stable PSE integration *Seung Park* (137)	Three-dimensional Richtmyer–Meshkov instability and turbulent mixing of a gas/liquid interface *Hong-Hui Shi* (137)	Low frequency instabilities in the initial merging zone of an annular jet *Maarten Vanierschot* (137)
4	Stability of an inverted spring pendulum driven by a periodic force *Moshe Gitterman* (269)	Numerical modelling of strain localization in glassy polymers recognising their intrinsic anisotropy *Huaxiang Li* (270)	Threshold behavior of Riemann curvature in non-euclidean continuous medium *Tatiana Nizkaya* (270)	Instability of compressible elastic materials at stretching stresses *Mikhail Karyakin* (270)
5	Meso-mechanical investigation on high temperature oxidation of thermal protective ceramics *Jun Liang* (278)	Influence of imperfect elastic contact condition on the effective properties of piezoelectric fibrous composites *Federico Sabina* (278)	The influence of the dimension ratio and interfacial debonding on plastic flow of cylindrical... *Ying Zhang* (278)	Accurate modelling of FRP composite sandwich plates having interlaminar slips *Anupam Chakrabarti* (279)
6	Experiment and simulation of unsteady sand mass flux in the near-surface layer *Ping Wang* (154)	Hydraulic modeling of runoff yield in small watersheds *Qingquan Liu* (154)	Thermodynamics of irreversible transitions in the oceanic general circulation *Shinya Shimokawa* (154)	A simple model to predict the seabed profile under pipelines *Lei Li* (155)
8	Symbolic tools for sensitivity analysis of multibody systems *Arnaud Sandel* (288)	Experimental analysis of the A-pillar vortex fluctuations *Benjamin Levy* (288)	Modelling and simulating automobile hysteresis nonlinear dynamical system *Mingxia Fang* (289)	On sensitivity methods for vehicle systems under stochastic crosswind-loads *Christian Wetzel* (289)
10	Global chaotic attitude dynamics of completely liquid-filled flexible spacecraft *Baozeng Yue* (350)	Blast propagation in domains of changing topology *Leonid Antanovskii* (350)	Evaluation of added mass coefficients of a hull form using Landweber *Hem Wadhwa* (350)	Improvement of aircraft rolling performance using piezoelectric actuators *Min Li* (351)

	Thu 14:30 Seminar	Thu 14:35 Seminar	Thu 14:40 Seminar	Thu 14:45 Seminar
A	A coarse particle method for nanoimprinting process *Cheng-Da Wu* (296)	Tuning acoustic wave properties by mechanical resonators on a surface *Maria Dühring* (296)	Theoretical analysis of three-point bending test of nanowires with surface effects *Xianwei Zeng* (297)	Failure prediction of single-walled carbon nanotubes under uniaxial tension using virial stress theorem *Tarek Ragab* (297)
11	An elastica approximate for fibers and fibrous networks *Carlos Castro* (342)	An inverse dynamic model of an arm via Kane's method: torque determin-ation in smash activity *Azmin Rambely* (343)	Forces on an adhering cell *Joseph Berry* (343)	Friction drag and pressure drag acting on an angled-wavy plate *Naoki Yoshitake* (343)
C	Topology optimization of continuum by successive approximation *Sei-ichiro Sakata* (313)	The optimum design of a rack and pinion gear using the Taguchi method *Sungpil Jung* (313)	**Control of structures** ▶	The adaptive spatial mobile robot-manipulator and way of diagnostics of physical and mechanical properties... *Sergey Sayapin* (217)
D	**Microfluidics** ▶	The efficiency of the coupled electrode-membrane processes in hydrogen fuel cell: thermodynamic analy-sis *Frantisek Marsik* (167)	Gas flows through shallow non-uniform microchannels *Amir Gat* (168)	Dewetting of nanometer thin films under an electric field *Guo-Hui Hu* (168)
E	Capillary ratchet: hydrodynamics of surface tension feeding in shorebirds *Manu Prakash* (116)	On the formation and cavity dynamics of big floating bubble by drop impact onto liquid pool *Chen-Chi Kuan* (117)	New types of a single bubble motions in dilute surfactant solution *Yoshiyuki Tagawa* (117)	Submerged gas jet interface stability *Chris Weiland* (117)
1	Experimental analysis on lower clamp bolt of motorcycle front fork during frontal impact *Shaw Wong* (268)	**Solidification and crystal growth** ▶	Analytical prediction of solidification in close-celled metal foams *Tongbeum Kim* (177)	Nano-scale solidification phenomena *Tomasz Kowalewski* (178)
2	A beam element for stability analysis of thin-walled frames with flexible connections *Goran Turkalj* (309)	Analysis on aeroelastic dynamics of a rotating laminated disk with viscoelastic core layer *Xingzhe Wang* (309)	Local lattice instability analysis on amorphous metals: effect of free surface *Masaomi Nishimura* (310)	**Mechanics of phase transitions** ▶
3	Linear stability analysis of secondary instability of boundary layer flow on a two-dimensional airfoil *Takashi Atobe* (137)	Instabilities in bluff plate boundary layers *Mark Thompson* (138)	Electrohydrodynamic instability in a horizontal Poiseuille flow with an electrical conductivity grad-ient *Min-Hsing Chang*(138)	Conditionally-sampled velocity in an oscillating-triangular-jet nozzle *Peter Lanspeary* (138)
4	Mathematical theory of accreted solids and its applications *Alexander Manzhirov* (271)	Onset of cavitation in compressible, isotropic, hyperelastic solids *Oscar Lopez-Pamies* (271)	Self-retracting motion and extreme anisotropy of graphite *Quan-shui Zheng* (271)	**Plasticity and viscoplasticity** ▶
5	**Cohesive zone models of fracture and failure** ▶	Influence of softening function on concrete fracture using cohesive crack model *Shailendra Kumar* (51)	A slip band based cohesive zone model for simulations of fatigue crack growth at sub-micron level *Xiaobo Yu* (51)	Cohesive zone model for intergranular stress corrosion cracking in ceramics *Marc de la Osa* (52)
6	New approach to mathematical modeling of admixture transport in free-surfaced streams *Konstantin Nadolin* (155)	**Experimental methods in fluid mechanics** ▶	A study in the effects of a new calibration technique on the 2D flow parameters *Mojtaba Manshadi* (124)	Experimental study of lid driven cavity flow in the Lagrangian frame of reference *Reut Elfassi* (124)
8	The multi-impact dynamics in multibody systems *Caishan Liu* (289)	**Chaos and pattern formation in fluid and solid mechanics** ▶	Acoustic chaos in sonic infrared imaging *Golam Newaz* (346)	Normal forms of Hamiltonian systems via curvature line transformations *Xinhua Zhang* (346)
10	Vortex-induced vibrations of a tethered sphere with neutral buoyancy *Hyeok Lee* (351)	Nonlinear vibration of a curved pipe conveying fluid subjected to tip harmonic excitation tangential to pipe center line *Ni Qiao* (351)	DQM for solving stability of a tubular cantilever conveying fluid downwards immersed in a cylindrical container *Qian Qin* (352)	Hydrodynamic behaviour characterization of vertical axis water turbine scale model *Nicolas Dellinger* (352)

	Thu 14:50 Seminar	Thu 14:55 Seminar	Thu 15:00 Seminar	Thu 15:05 Seminar
A	On the modelling and decomposition of gradient enhanced electro-mechanically coupled deformation *Sebastian Skatulla* (297)			
B				
C	Distributed control of plate vibrations induced by in-plane time-dependent forces *Andrzej Tylikowski* (217)			
D	On penalty approaches for Navier-slip and other boundary conditions in viscous flow *Yvonne Stokes* (168)	Capillary driven flows: velocity dependent contact angles and chemically patterned walls *Mihail Popescu* (169)	Hydrodynamic friction of a polymer adsorbed on a planar surface *Krzysztof Sadlej* (169)	
E	**Classical and quantum vortex rings** ▶	Global time evolution of an axisymmetric vortex ring at small Reynolds numbers *Felix Kaplanski* (73)		
1	Phase-field simulation for the growth of boride (Fe2B) phase from austenite phase *Raden Ramdan* (178)			
2	Thermomechanical properties of shape-memory polymer and composite *Hisaaki Tobushi* (282)	Atomic-scale mechanism of crack-tip deformation: twinning and phase transformation *Ya-Fang Guo* (282)		
3	Stability of plane Poiseuille flow of a fluid with pressure-dependent viscosity *Thien Tran* (139)	Vortex structure in an oscillating-triangular-jet nozzle *Soon-Kong Lee* (139)		
4	Influence of die rotating speed on forward extrusion *Xiang Ma* (304)	An influence of torsional cycles on the uni-axial tension of selected materials *Zbigniew Kowalewski* (304)	The relationship between deformation-induced texture *Long Shiguo* (305)	
5	Solution strategy for large three-dimensional composite structures with geometric and material instability... *Lars Overgaard* (52)			
6	Prediction of aerodynamic coefficients of a plunging airfoil using neural networks *Feazeh Marzabadi* (124)			
8	Bifurcation and chaos in drive systems *Martin Houfek* (347)	**Stirring and mixing** ▶	Chaotic thermal mixing in a two rod mixer *Kamal El Omari* (180)	
10	Simulation of unsteady hydrodynamic loadings and structural analysis of vertical axis water turbine *Jeronimo Zanette* (352)	Impact of a spherical shell on a thin layer of the water *Tatiana Khabakhpasheva* (352)	Dynamics of fluid-conveying pipes: effects of velocity profiles *Stephanie Enz* (353)	Impinging jets on a plate with a degree of freedom in torsion *Yohann Nyirumulinga* (353)

			Thu 16:00 Lecture	Thu 16:20 Lecture	Thu 16:40 Lecture
A	**Poster viewing and coffee :: Thu 15:10–16:00 Hall K**	**Mechanics of material processing** ▶	Supercritical bifurcation in the state-dependent delay model of turning *Pankaj Wahi* (361)	Apparent coexistence of multiple regimes of self-excited vibrations in deep drilling systems *Emmanuel Detournay* (361)	Bi-stable region estimations for metal cutting *Gabor Stepan* (361)
B		**Flow control** ▶	Estimation of the potential of a flow-control experiment by system identification *Fredrik Lundell* (127)	Wake flow manipulation by means of blowing or suction *Jens Fransson* (128)	Optimal control of vortex systems *Bartosz Protas* (128)
C		**Drops, bubbles and multiphase flows** ▶	Memory-encoding shape vibrations in a disconnecting air bubble *Wendy Zhang* (118)	Geometric confinement suppresses jet break-up in microfluidic channels *Katherine Humphry* (118)	Discontinuous flow in the thinning process of viscoelastic filaments *Christian Wagner* (118)
D		**Granular materials and flows** ▶	Computer aided kinetic theory and granular matter *Isaac Goldhirsch* (359)	Realization of the Smoluchowski–Feynman ratchet in a granular gas *Devaraj van der Meer* (359)	The numerical simulation for a hemisphere colliding into granular material *Lei Yang* (359)
E		**Porous media** ▶	The three characteristic behaviours of dual-porosity media *Pascale Royer* (365)	Exact infiltration under concentration boundary conditions *Philip Broadbridge* (365)	Kinetic theory for suspension/colloid flow in porous media *Pavel Bedrikovetsky* (366)
1		**Flow in thin films** ▶	Flow structure in free surface film and Couette flow over non-planar substrates *André Haas* (146)	3D waves on liquid films and rivulets flowing down vertical plate *Sergey Alekseenko* (146)	Rupture of a current-carrying fluid cylinder *Jonathan Mestel* (146)
2		**Low-Reynolds-number flow** ▶	Periodic fundamental solution of the two-dimensional Stokes flow *Hidenori Hasimoto* (161)	Dynamics of the snail ball *William Young* (161)	Low Reynolds number swimming beneath a free surface *Darren Crowdy* (162)
3		**Magnetohydrodynamics** ▶	The helical magnetorotational instability in cylindrical Taylor–Couette flow *Rainer Hollerbach* (165)	The helicities and group velocities of unstable modes generated by tidal effects *Krzysztof Mizerski* (165)	Turbulent MHD channel flow with spanwise magnetic field *Thomas Boeck* (165)
4		**Contact and friction mechanics** ▶	Contact vibration analysis of an elastic-sphere oscillator and a semi-infinite viscoelastic cubic solid *Jiayong Tian* (214)	Three-dimensional contact of rough bodies by multiply-connected domain *Ganna Shyshkanova* (214)	Friction mechanism of an elastomer sliding on smooth surface: influence of water squeeze film *Deleau Fabrice* (214)
5		**Stirring and mixing** ▶	Speeding up mixing with moving walls *Jean-Luc Thiffeault* (180)	The prevalence of ghost rods in batch mixer designs *Stephen Cox* (181)	Advection of passive fluid by periodical injection from a two-dimensional flat chink *Alexandre Gourjii* (181)
6		**Stability of structures** ▶	Stress focusing in twisted thin elastic plates *Ciprian Coman* (310)	Large deformation and instability in hydrogels *Zhigang Suo* (310)	The initiation of strain nonuniformity in thin–walled cylinders subjected to cyclic torsion analogous... *Masami Kobayashi* (311)
8		**Microfluidics** ▶	Controlled cavitation and sonoporation in microfluidics *Pedro Quinto Su* (169)	Free surface microfluidics for explosives detection *Brian Piorek* (170)	Fabrication of a nanofluidic field effect transistor for controlled cavitation in nanochannels *Egbert van der Wouden* (170)
10		**Nanostructures and MEMS** ▶	Higher-order equations for quantum dot structures in thin solid films *Peter Evans* (298)	Application of molecular statistical thermodynamics to uniaxial tension of ZnO nanorods *Yilong Bai* (298)	Theoretical analysis of adsorption-induced microcantilever bending *Shou-Wen Yu* (298)

		Fri 08:30 Lecture		Fri 09:15 Lecture
A	**Fluid Mechanics Sectional Lectures** ▶	The aerodynamics of wind turbines *Jens Sørensen* (40)	**Flow instability and transition** ▶	Flow destabilization and chaotic mixing in the channel with transversely corrugated walls *Slawomir Blonski* (139)
B	**Solid Mechanics Sectional Lectures** ▶	Micro-architectured solids: from blast resistant structures to morphing wings *Norman Fleck* (43)	**Acoustics** ▶	Wolf killing: the subtle problem of controlling cello string/body coupled resonances *Antunes Jose* (328)
C	**Fluid Mechanics Sectional Lectures** ▶	Onset of oscillatory thermocapillary convection *Wenrui Hu* (40)	**Drops, bubbles and multiphase flows** ▶	Impact of drops of complex liquids on a small target *Michele Vignes-Adler* (118)
D	**Solid Mechanics Sectional Lectures** ▶	Maximal information systems *Hugh Durrant-Whyte* (42)	**Experimental methods in fluid mechanics** ▶	Optically interrogated MEMS pressure sensor array *Lukas Prochazka* (125)
E	**Fluids and Solids Sectional Lectures** ▶	Instabilities of flows through deformable tubes and channels *Oliver Jensen* (45)	**Structural optimization** ▶	Error estimate based remeshing strategy for shape optimization using radial basis functions *Daniel Wilke* (314)
1			**Geophysical and environmental fluid dynamics** ▶	Evidence of anisotropy of small scale turbulence in the laboratory model of an atmospheric cloud *Piotr Korczyk* (155)
2			**Mechanics of material processing** ▶	Study of material behaviour at large plastic strains using plane-strain machining with a wedge indenter *Tejas Murthy* (362)
3			**Multibody and vehicle dynamics** ▶	Analytical study of the improved seatbelt retractor *Chanseung Park* (289)
4			**Elasticity** ▶	Continuum modeling of elastic dielectric solids with defects, with application to barium strontium titanate thin films*John Clayton* (233)
5			**Turbulence** ▶	Scaling regimes of the 2D Navier–Stokes equation with self-similar stirring *Paolo Muratore-Ginanneschi* (189)
6			**Flow in thin films** ▶	Resonance of surface waves in gravity-driven films over undulated bottoms *Christian Heining* (147)
8			**Mechanics of phase transitions** ▶	Stress-induced martensitic phase transformation in Nitinol *Samantha Daly* (282)
10			**Fluid-structure interactions** ▶	Linear analysis of boundary layer flow interacting with a finite compliant surface *Mark Pitman* (353)

	Fri 09:35 Lecture	Fri 09:55 Lecture	Fri 10:15 Lecture		
A	Dynamics of a fluid inside a precessing cylinder *Romain Lagrange* (140)	Primary and secondary instability of the boundary layer in a rotating annulus *Bertrand Viaud* (140)	Poincaré section analysis of an experimental frequency intermittency in an open cavity flow *François Lusseyran* (140)	**Coffee break :: Fri 10:35–11:00 Hall K**	**Flow instability and transition** ▶
B	Acoustic properties of dry and saturated porous media *Pierre Adler* (329)	Acoustics of streaming: a mechanism of noise generation in subsonic jets *Xuesong Wu* (329)	The “two-phase sound” of cheering champagne glasses *Debut Vincent* (329)		**Structural vibrations** ▶
C	Translational dynamics of an acoustically coupled microbubble pair in an ultrasound field *Michel Versluis* (119)	Bubble/microcantilever interactions in a confined channel *Ellen Longmire* (119)	Direct simulation of unsteady three-dimensional core-annular flows with high viscosity ratio *Jie Li* (119)		**Drops, bubbles and multiphase flows** ▶
D	Planar imaging measurements of molecular transport effects in turbulent mixing *Lester Su* (125)	An efficient correction for the finite-size effects of multihole pressure probes in velocity gradients *Valery Chernoray* (125)	Measurements of the dynamic wall-shear stress distribution in turbulent flows using MPS^3 *Sebastian Grosse* (126)		**Experimental methods in fluid mechanics** ▶
E	Optimum material design of maximum structural seepage under compliance constraint *Gengdong Cheng* (314)	Topology optimization of optical band gap effects in slab structures modulated by periodic Rayleigh waves *Niels Aage* (314)	Optimization of stepped beams and plates *Jaan Lellep* (315)		**Stirring and mixing** ▶
1	Particulate gravity currents along v-shaped valleys *Joe Monaghan* (156)	On numerical simulation of tropical atmospheric intraseasonal oscillation (MJO) *Jian Ling* (156)	Separating flow over two-dimensional rough hills *Juliana Loureiro* (156)		**Fluid-structure interactions** ▶
2	Supercritical bifurcations in the state-dependent delay model of turning process *Tamás Insperger* (362)	Numerical simulation of friction stir welding processes *Elias Cueto* (362)			**Computational solid mechanics** ▶
3	The dynamic characteristic analysis of the bi-modal tram using the test platform of all wheel steering ECU *Sooho Lee* (290)	Discrete time transfer matrix method for dynamics of multi-rigid-flexible-body system *Xiaoting Rui* (290)	Coupled simulation of dispersions in multibody systems *Peter Eberhard* (290)		**Multibody and vehicle dynamics** ▶
4	Mathematical modeling of linearly piezoelectric slender rods *Thibaut Weller* (233)	Internal variables and microstructured materials *Juri Engelbrecht* (233)	Analysis of interfacial crack by means of hypersingular integro-differential equations *Noda Nao-Aki* (234)		**Structural optimization** ▶
5	Discussion on the rapid pressure–strain correlation in the rapid distortion limit *Song Fu* (190)	Gradient statistics in the shearless turbulent mixing *Daniela Tordella* (190)	Large eddy simulations of a self-similar mixing layer using the stretched-vortex subgrid model *Trent Mattner* (190)		**Experimental methods in solid mechanics** ▶
6	Centrifugally driven thin film flow over a fast rotating cone with arrays of micron sized holes *Paul Duineveld* (147)	Unsteady contact melting *Tim Myers* (147)			**Flow control** ▶
8	Guided phase pattern formation in monolayers *Wei Lu* (282)	An elastoplastic phase field model for microstructure evolution *San-Qiang Shi* (283)	Discrete dislocation-transformation model for austenitic single crystals *Sergio Turteltaub* (283)		**Granular materials and flows** ▶
10	The fluid–structure dynamics of a cantilevered-free flexible plate in a uniform flow *Anthony Lucey* (354)	Nonlinear mixed-mode lateral vibration of a fluid-conveying cantilevered pipe with an end mass *Masatsugu Yoshizawa* (354)	Chaotic oscillation during vortex-induced vibration *Justin Leontini* (354)		

	Fri 11:00 Lecture	Fri 11:20 Lecture	Fri 11:40 Lecture	Fri 12:00 Lecture
A	Symmetry breakings in the wake of a disk: a global stability analysis *Philippe Meliga* (141)	Spatial optimal disturbances in swept attachment-line boundary layers *Patrick Huerre* (141)	Spatial-temporal stability of mixed forced-free convection boundary layers *Eunice Mureithi* (141)	On the instability of vortices embedded in shear flows *Philip Hall* (142)
B	VIV of vertical offshore riser in lock-in: low-dimensional model *Marian Wiercigroch* (324)	Dynamic analysis of an automatic transmission parking mechanism *Jeku Jeyakumaran* (325)	Amplitude reduction of self-excited micro-cantilever probe of atomic force microscope *Hiroshi Yabuno* (325)	Classification of non-smooth bifurcations for a friction oscillator *Hans Troger* (325)
C	Interaction of a shock wave with multiple gas bubbles in water *Stephen Shaw* (120)	Liquid effects on the unsteady motion of a collision-dominant solid-liquid flow... *Fu-Ling Yang* (120)	Evolution of neutral and charged drops in an electric field *Ultano Kindelan* (120)	Electrophoresis of gas bubbles *John Harper* (121)
D	Heterodyne Doppler global velocimetry *Alexander Meier* (126)	Large spatial dynamic range measurements of a turbulent boundary layer and the velocity gradient tensor... *Craig Dillon-Gibbons* (126)		
E	Laminar mixing of fluids and scalars: a unified Hamiltonian approach *Michel Speetjens* (181)	Mixing of polymer solution in curvilinear pipe *Shinji Tamano* (182)	Stirring with ghost rods in counter-rotating flows *Mark Stremler* (182)	
1	Oscillation onset in collapsible tubes by decreasing external pressure *Christopher Bertram* (354)	Analytical model for the lift on a rotationally oscillating cylinder *Muhammad Hajj* (355)	Third-order effects in wave–body interaction *Bernard Molin* (355)	Phase shift effects for fluid conveying pipes with non-ideal supports *Jonas Dahl* (355)
2	Morphology change in interfacial dislocation network by prismatic dislocation loop... *Kisaragi Yashiro* (208)	A new curved FE approach for analysis of masonry vaults *Antonio Tralli* (208)	Anisotropic hyper-elastic shells using polyconvex strain energy function with application to mechanical cloth... *Masato Tanaka* (209)	Inverse analyses, artificial neural networks and dilatometric tests for damage assessment in concrete dams *Giulio Maier* (209)
3	Free vibration of vehicles with interconnected suspensions *Wade Smith* (291)	Motion of an inertially excited two-mass oscillator along a rough plane *Igor Zeidis* (291)	Helix beam finite element based on intrinsic spatial curvatures *Oleg Dmitrochenko* (291)	Roll-tracking control of an unmanned bicycle using fuzzy logic controller *Chih-Keng Chen* (292)
4	Structural optimization using evolutionary algorithm and data mining *Ting-Yu Chen* (315)	Level set approach for structural optimization *Andrzej Myśliński* (315)	Structural shape optimization by weight of NURBS with IGES file exchange *Geol Choi* (316)	Manufacturing tolerant topology optimization for MEMS design *Ole Sigmund* (316)
5	Measuring deformation of large vessels with innovative broken-ray videometrics *Yu Qifeng* (240)			
6	Active control of flow with trapped vortices *Owen Tutty* (128)	Dynamic roughness actuation of a turbulent boundary layer *Beverley McKeon* (128)	Synchronized force and PIV measurements on an electromagnetically forced separated flow *Christian Cierpka* (129)	Low-order estimation and modeling of transient growth in a laminar boundary layer *Jonathan Morrison* (129)
8	A multiscale methodology in granular matter physics *Qicheng Sun* (359)	Nonlinear stability of granular shear flow: Landau equation and shear-banding *Meheboob Alam* (360)	Pattern formation at a sand bed surface *Thomas Loiseleux* (360)	
10				

		Fri 12:25 Lecture	
A			**Lunch :: Fri 13:25–14:25**
B			
C			
D			
E	**Closing Lecture** ▶	Physical limnology: advances and future challenges *Jorg Imberger* (36)	
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OL :: Opening Lecture

Chair: Viggo Tvergaard (Denmark)

Mon	10:00–11:00	Hall E	Lecture

The role of mechanics in advancing thermal barrier coatings

10307
Mon·10:00·E

John Hutchinson
Harvard University, USA

Thermal barrier coatings are now used throughout the hottest sections of all aircraft and power generating gas turbine engines to coat superalloy blades and structural components. The coatings are multilayers consisting of a low thermal conductivity porous ceramic thermal barrier, a very thin alumina layer that serves as an oxidation barrier, and a metallic layer providing good bonding to the superalloy component. Thermal barrier coatings now provide the major opportunity for improving engine efficiency through increases in temperature. The lecture will provide a broad overview of the considerable range of activities on the mechanics of thermal barrier coatings covering experimental and theoretical aspects, including basic work to link the macroscopic properties that determine durability to the atomistics of multilayer interfaces.

CL :: Closing Lecture

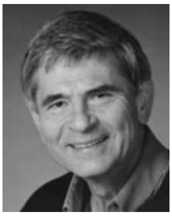
Chair: Ernest Tuck (Australia)

Fri	12:25–13:25	Hall E	Lecture

Physical limnology: advances and future challenges

10308
Fri·12:25·E

Jorg Imberger
University of Western Australia, Australia



Over the last 30 years, limnology has become a mature field with most of the energy flux paths now well established and incorporated into 3D models. The energy from the wind and the sun enters a lake via the free surface, the river inflow may form overflows, intrusions or underflows and the selectivity of a withdrawal flow depends strongly on the thermal stratification in the lake. The talk is structured to follow the energy flux from the wind, to surface waves and surface layer turbulence, to basin scale barotropic lake seiching and internal waves, to high frequency free internal waves and free gyres, to the benthic boundary layer to finally the intermittent turbulence field in the water column; this is generated by non linear wave breaking, Kelvin Hemholz billowing and Holmboe shear instabilities, depending on the relative placement of the shear and density field gradients. Inflows and outflow dynamics is then briefly reviewed. Next, I show how this symphony of motions adds to sustain a weak vertical mass flux and a horizontal dispersion; the latter being critically dependent on the topology of the horizontal residual circulation and the presence of unsteady stagnation points. I will conclude with an illustration of how the full complexity of these motions can be captured with a 3D model that also beautifully illustrates the competitive nature of the various components of the motion in determining the net mixing in a lake and I show how this competition is a strong function of the lake and stratification properties.

BL :: Batchelor Prize Lecture

Chair: Timothy Pedley (UK)

Wed	08:30–09:25	Hall E	Lecture

Interfaces: in fluid mechanics and across disciplines

12103
Wed·08:30·E

Howard Stone
Harvard University, USA

Interfaces play an important role in many fluid mechanics problems. Here we recognize (i) fluid-solid interfaces and how their microstructure can influence fluid flows, (ii) fluid-fluid systems where interfacial tension and surface viscous effects can impact, or control, fluid flows, and (iii) interfaces between traditional disciplines that so often are the source of new questions in mechanics.

HL :: Rodney Hill Prize Lecture

Chair: Bernhard Schrefler (Italy)

Wed	08:30–09:25	Hall D	Lecture

Nonconvex plasticity and deformation microstructures

12042
Wed·08:30·D

Michael Ortiz
California Institute of Technology, USA

The mathematical theory of plasticity, which Rodney Hill made seminal contributions to, traditionally insisted on convexity as a means of ensuring uniqueness of solutions of the incremental problem. Often, as in Drucker's postulates, the assumption of convexity was expressed in the language of thermodynamics, which lent it the appearance of a fundamental physical principle. Classical plasticity is a well-developed field and the assumption of convexity is central to many of the classical theorems of plasticity. By contrast, as recently as the late nineties, non-convex plasticity was, for the most part, terra ignota in the mathematical theory of plasticity. It is remarkable that so late in the development of a theory there should remain so much unknown territory to explore. Indeed, as has recently become clear, many of the deformation microstructures that are observed experimentally can be rationalized mathematically as consequences of lack of convexity. Early glimpses of this connection were provided by strain-localization analysis (lack of rank-one convexity, in modern parlance) and by computational studies. However, a robust mathematical link between deformation microstructures and non-convexity (localization analysis just provides a peek into the onset of a limited type of material instabilities) would have to await the application of the modern tools of calculus of variations, developed in the mathematical community by such giants as C. B. Morrey and E. de Giorgi. The first step in forging that connection is to formulate the problem of plasticity as a bona fide minimum problem. This formulation can be accomplished by recourse to time discretization, e.g., through the classical theory of minimal paths; or by recourse to energy-dissipation functionals, whose minimizers describe entire trajectories of the system including microstructural evolution. In ductile single crystals the functionals to be minimized turn out to be non-convex (non-Druckerian!) owing to two main physical reasons: geometrical softening and strong latent hardening. Modern tools of the calculus of variations, such as relaxation, Gamma-convergence and optimal scaling can then be applied to great advantage to determine: optimal deformation microstructures such as cell structures, fence structures, labyrinthic structures, lamellar structures, dislocation pile ups and others as a function of material parameters, loading conditions and geometrical features such as grain size; the macroscopic effective behavior of the material resulting from the formation and evolution of the microstructures; and attendant scaling relations such as Hall–Petch scaling and Taylor hardening.

FL :: Fluid Mechanics Sectional Lectures

Chairs: Eberhard Bodenschatz (Germany), Jacques Magnaudet (France), Jean-Marc Vanden-Broeck (UK), Ross Griffiths (Australia) and André Thess (Germany)

Tue	08:30–09:15	Hall B	Lecture
Wed	09:25–10:10	Hall B	Lecture
Wed	09:25–10:10	Hall C	Lecture
Thu	08:30–09:15	Hall B	Lecture
Fri	08:30–09:15	Hall C	Lecture
Fri	08:30–09:15	Hall A	Lecture

Nonlinear transient growth on a vortex column

10310
Tue·08:30·B

Fazle Hussain[†] and Dhoorjaty Pradeep
University of Houston, USA[†]

We study transient growth of perturbations on the Oseen vortex via direct numerical simulations. The modes of greatest practical interest are the bending waves, which generate significant core distortion through a resonance mechanism. Resonance occurs when the external perturbations are localized at a critical radius where the mean azimuthal velocity matches the wavespeed of a Kelvin wave in the core. With increasing initial amplitude, the maximum energy amplification and the growth period are reduced from those for infinitesimal perturbations. Remarkably, even a single bending wave optimal mode captures the key features of vortex-turbulence interaction: growth of strong core perturbations, mean circulation overshoot, and dipole formation and radial spreading of external turbulence. Turbulence levels and energy gains increase with increasing *Re*. Thus transient growth is likely to govern turbulent vortex decay, of interest in high-*Re* practical flows such as the aircraft wake.

Bubbles in micro- and nano-fluidics

10311
Wed·09:25·B

Detlef Lohse
University of Twente, Netherlands

Bubble nucleation at surfaces is a poorly understood phenomenon. We did visualization experiments at hydrophobic surfaces structured at the microscale and compared the results with both boundary integral simulations and Rayleigh–Plesset type model calculations, in particular focusing on bubble-bubble interactions. It is demonstrated that in the many bubble case the bubble collapse is delayed due to shielding effects. We succeed in making cavitation totally reproducible in space and time. When reducing the surface structure by a factor of 10 to about 100nm, one reaches the scale of the so-called surface nanobubbles. These are structure seen in atomic force microscopy (AFM) images. We will give evidence that these structure are indeed bubbles and will analyse the conditions under which they form. However, we find them to be stable against massive pressure reduction: Surprisingly, their appearance is uncorrelated with bubble nucleation events on the surface.

Capillary constructions

10315
Wed·09:25·C

David Quéré
Ecole Supérieure Physique et de Chimi Industrielles, France

No abstract was provided.

Indian Ocean Dipole and its possible link with climate modes **11053**

Thu·08:30·B

Toshio Yamagata
Japan Agency for Marine-Earth Science and Technology, Japan

Tropical oceans give birth to climate modes that play major roles in climate variability under the global warming stress. The well-known El Nino/Southern Oscillation (ENSO) in the tropical Pacific is one of such climate modes. About a decade ago, another vigorous climate mode was identified in the Indian Ocean, which is now widely accepted as the Indian Ocean Dipole. A prominent feature of IOD is the characteristic east-west dipole pattern in sea surface temperature (SST) anomalies, heat content/sea level anomalies, outgoing longwave radiation (OLR) anomalies and sea level pressure anomalies. Those anomalous conditions imply existence of a Bjerknes feedback mechanism during the evolution of IOD. Through atmospheric and oceanic bridges, those climate modes interact with each other and influence the world climate in a complex way. In my presentation, I will review the state-of-the-art understanding of IOD with special attention to its interaction with ENSO.

Onset of oscillatory thermocapillary convection **10309**

Fri·08:30·C

Wenrui Hu
Chinese Academy of Sciences, China

Thermocapillary convection is an important subject of nature convection in the microgravity environment, and dominates many processes in the space materials processing and space biotechnologies. The onset of oscillatory convection relates to the transition and bifurcation of fluid system. The space experiments and simulation experiments of small scale on the ground are summarized to search the critical parameters for onset of oscillatory thermocapillary convection. The theoretical models are analyzed for discussion of the mechanisms. The results show that, the subject is still open for future research, and several space experiments are arranged to be performed in the near future.

The aerodynamics of wind turbines **10312**

Fri·08:30·A

Jens Sørensen
Technical University of Denmark, Denmark

From an outsider's viewpoint, the aerodynamics of wind turbines may seem simple compared with the aerodynamics of fixed-wing aircraft or helicopters. However, wind turbines have several added complexities. Most prominently, aerodynamic stall is always an intrinsic part of the wind turbine's operational envelope. When separation occurs, outward spanwise flow generated by centrifugal pumping tends to decrease the boundary layer thickness, resulting in the lift coefficient being higher than what would be obtained on a non-rotating blade. When the wind changes direction the assumption of axisymmetric inflow conditions is no longer valid and gives rise to radial flow components in the boundary layer. Thus, both the airfoil characteristics and the wake are subject to complicated three-dimensional and unsteady flow behaviour. In the presentation I will give a state-of-the-art within the aerodynamics of wind turbines, focussing on issues relating to blade aerodynamics and wake dynamics.

SL :: Solid Mechanics Sectional Lectures

Chairs: Carl Herakovich (USA), Hans Muhlhaus (Australia), Nikita Morozov (Russia), Robert McMeeking (USA), Graham Weir (New Zealand) and Werner Schiehlen (Germany)

Tue	08:30–09:15	Hall D	Lecture
Wed	09:25–10:10	Hall A	Lecture
Wed	09:25–10:10	Hall D	Lecture
Thu	08:30–09:15	Hall A	Lecture
Fri	08:30–09:15	Hall D	Lecture
Fri	08:30–09:15	Hall B	Lecture

Self-healing materials systems: where mechanics meets chemistry

10319
Tue·08:30·D

Nancy Sottos
University of Illinois at Urbana-Champaign, USA

Self-healing materials are inspired by living systems in which minor damage triggers an autonomic healing response. This lecture summarizes three approaches to achieve self-healing and highlights the critical roles of mechanics and polymer chemistry in the development of these novel materials. In the first approach, crack damage triggers the release of encapsulated healing agents stored in the material. Although the encapsulated approach to self-healing yields high healing efficiencies, the number of possible healing events is limited by the finite supply of healing agent in the capsules. A second approach provides a solution to the limited supply of healing agent through incorporation of a microvascular network to replenish the healing chemistry whenever damage occurs. A third molecular-based self-healing approach is under development, which relies on mechanochemical activation of special molecules linked directly in the polymer backbone, without the need for stored healing agents.

Characterization of heterogeneous materials by multi-scale simulations

10061
Wed·09:25·A

Peter Wriggers
University of Hannover, Germany

This lecture focuses on different formulations and associated simulation techniques that can be used to obtain effective properties of heterogeneous and granular materials. Detailed investigations are related to the micromechanical modeling of cement paste based on microstructures from CT scans. Effective properties are determined by stochastic numerical simulations and inelastic constitutive relations are provided for micro- and macro-scale. Damage of the cement paste due to frost is considered using homogenization techniques as a true multiscale approach. Adaptive multiscale resolution analysis of microheterogeneous structures that exhibit localization zones where standard homogenization techniques may fail are also considered. A central goal is to adaptively identify multiple regions of macroscale structural resolution in order to improve the accuracy and reliability of macrostructural analyses and to provide a method that can incorporate distinct cracks in three-dimensional FEA.

Failure of rocks in the laboratory and the Earth

10318
Wed·09:25·D

John Rudnicki
Northwestern University, USA

The vast majority of tests on rocks have been done in axisymmetric configurations in which two of the principal stresses are equal. This severely limits the deviatoric stress states that are accessible and makes it difficult to distinguish between various predictions of failure stress and the orientation of the failure plane. Although K. Mogi did pioneering work on true triaxial testing (all three principal stresses are different) in the 1960's, there has been little systematic work on this subject since then. Recently, however, Haimson and coworkers have conducted a series of true triaxial tests on several rock types. This lecture will describe work in progress to interpret these data to gain additional insight into rock failure and to compare observations with predictions of failure, including those from the theory of localization of deformation, and models of inelastic deformation of rock.

Plasto-mechanics of large deformation under impact loading

10317
Thu·08:30·A

Narinder Gupta
Indian Institute of Technology, Delhi, India

Plasto-mechanics of large deformation is inherently complex. There is a lack of understanding of the phenomenon and its dependence on various parameters like strain rate, inertia, history of loading, annealing and thermal processes and geometry. Mechanics of large deformation in relation to absorption of kinetic energy of external impact loading has been studied over the years through several experimental, analytical and numerical researches. Many problems relating to deformation modes and their dependence on various parameters, however, are yet to be resolved. Structured experiments are of help to study the phenomenon and provide plausible explainations, assumptions and parameters needed for its realistic analysis. In this sectional lecture, I share some of the observations made in studies carried out to help in understanding the phenomenon and its dependence on different parameters.

Maximal information systems

10013
Fri·08:30·D

Hugh Durrant-Whyte
University of Sydney, Australia

Information provides a quantitative metric for describing the value of individual systems components in autonomous systems tasks such as tracking, mapping and navigation, search and exploration. An information model is an abstraction of system capabilities in an anonymous form which allows a priori reasoning on the system itself. By construction, information measures have properties of composability and additivity and thus provide a natural means of modelling and describing large-scale systems of systems. This talk will begin by describing how information measures arise naturally in autonomous tracking, mapping and navigation, search and exploration tasks. It is then demonstrated that the performance of individual sensors and platforms can be modelled using these information measures and that system-level performance metrics can be computed. These ideas are illustrated in a series of tasks involving mixed air and ground autonomous systems.

Micro-architectured solids: from blast resistant structures to morphing wings

10316
Fri·08:30·B

Norman Fleck
University of Cambridge, UK

Lattice materials are periodic, micro-architectured cellular solids, with a wide range of property and potential application. Examples range from the 2D hexagonal honeycomb to 3D Kagome lattices. The static and dynamic properties of these materials are explored, and their potential applications are reviewed. Insight to their response is obtained by analysing the equivalent, rigid, pin-jointed truss. For example, statically and kinematically determinate pin-jointed trusses give rise to rigid-jointed lattices with useful morphing properties: upon replacement of one or more bars by an actuator, the lattice can undergo large shape changes with negligible resistance. Yet, when the actuators are locked, the lattice is stiff to external loading. This feature is illustrated for 2D Kagome lattices, double layer grids with Kagome faces and cores and hollow circular tubes with lattice walls made from a fully triangulated lattice sheet.

FSL :: Fluids and Solids Sectional Lectures

Chairs: Dominique Barthès-Biesel (France), Tom Mullin (UK), Gary Leal (USA), Kaushik Bhattacharya (USA) and Patrick Huerre (France)

Tue	08:30–09:15	Hall C	Lecture
Tue	08:30–09:15	Hall A	Lecture
Thu	08:30–09:15	Hall D	Lecture
Thu	08:30–09:15	Hall C	Lecture
Fri	08:30–09:15	Hall E	Lecture

From dry granular flows to submarine avalanches

10017
Tue·08:30·C

Olivier Pouliquen
Polytech Marseille, France

Those who have played with sand on the beach or with sugar in their kitchen are aware that a collection of solid grains can behave macroscopically like a liquid and flow. However, the description of this peculiar fluid still represents a challenge due to the lack of constitutive laws able to describe the rich phenomenology observed. This talk will first review the properties of dry granular flows and will present recent advances in our understanding of their rheological behavior. The success and limits of a simple visco-plastic model recently developed will be presented. The second part of this presentation will discuss the more complex case of mixture of grains and liquid, and will show how the recent progresses obtained in the dry case allow to better understand immersed granular flows such as those encountered in submarine avalanches.

Biomechanical aspects in human reproduction

10471
Tue·08:30·A

David Elad
Tel Aviv University, Israel

Human reproduction depends on a number of transport vehicles. The detached ovum is transported to the fallopian tube. The spermatozoa are transported to the fallopian tube where fertilization may occur. The newly born embryo (zygote) is driven to the uterine cavity, and is then conveyed to its implantation site in the uterine wall. The fetus exchanges materials with the environment via the placenta and maternal blood circulation. At term, uterine contractions push out the baby. The presentation will cover bioengineering studies on the role of uterine peristalsis in embryo transport to its implantation site; the transport characteristics of embryos during their return to the uterus after laboratory fertilization; analysis of placental feto-maternal circulation for early diagnosis of placenta insufficiency; the electro-mechano-physiology of myometrial smooth muscles; and biomechanics of embryonic development.

Material instabilities in elastic and plastic solids **10014** Thu·08:30·D

Davide Bigoni
University of Trento, Italy

The perturbative approach to material instability proposed by Bigoni and Capuani (J. Mech. Phys. Solids, 2002; 2005) consists in the analysis of the response to an incremental perturbation of a uniformly deformed infinite body subject to remote, finite strain. The approach is shown to reveal features which remain undetected using conventional methods based on local stability criteria, for instance, it provides a mechanical interpretation to flutter instability in a continuum. Different perturbing agents can be employed, namely, concentrated forces and dipoles, fractures and rigid inclusions. These agents can also be randomly distributed and may simulate long-range effects of a dislocation distribution. Finally, the perturbative approach permits analytical solution for a finite-length shear band in an infinite prestressed material subject to Mode II loading, providing justification of the experimental observation that shear bands are preferred failure modes in ductile materials.

Cellular matter: interfacial mechanics and geometry **10015** Thu·08:30·C

Sascha Hilgenfeldt
Northwestern University, USA

Patterns and structures on the micro- and nanoscale are a key focus of today's quantitative sciences, emphasizing the importance of the interfaces between structural elements. In the limit where free energy is dominated by interfacial terms, we speak of Cellular Matter, made up of space-filling building blocks such as grains, droplets, bubbles, or cells. We review and highlight the intimate connection between cell geometry and the physical, mechanical, and functional properties of the material. One system we focus on here is liquid foam, which offers exceptional access and control to both experiment and theory. Another is cells in epithelial tissues: Recently, we successfully demonstrated quantitative modeling of the geometry of Drosophila retinal tissue using an interfacial energy formalism. In these biological systems, membrane elasticity and adhesion biochemistry add interesting wrinkles to the general approach and indicate a rich area of new applications for interfacial mechanics.

Instabilities of flows through deformable tubes and channels **10016** Fri·08:30·E

Oliver Jensen
University of Nottingham, UK

The motion of air and other liquids in lung airways, or blood in veins and arteries, can be strongly influenced by interactions between hydrodynamic forces and elastic (and sometimes muscular) forces in the vessel wall. These interactions generate a variety of instabilities, including familiar examples such as wheezing and flow limitation in asthma. Theoretical models and experiments have shown how single-phase flow, driven through a segment of flexible tube, is subject to distinct modes of self-excited oscillation spanning a wide range of frequencies. I will explain how a high frequency mode can be captured via rigorous high-Reynolds-number asymptotics, supported by computation, allowing the global energy budget to be tracked and revealing connections with underlying local modes and the critical role of boundary conditions. I will also explain how simplified models capture the overall dynamics of this system and extensions involving multiphase flows.

MS01 :: Cohesive zone models of fracture and failure

Chairs: Thomas Siegmund (USA) and Alberto Carpinteri (Italy)

Mon	11:00–13:00	Hall C	Lectures
Tue	09:15–09:55	Hall C	Lectures
Tue	10:40–12:40	Hall C	Lectures
Tue	16:00–17:40	Hall C	Lectures
Thu	14:35–14:55	Room 5	Seminars

Modelling of bone failure by cohesive zone models: nano- and microscale

10081
Mon·11:00·C

Thomas Siegmund
Purdue University, USA

Cohesive zone models are a powerful tool for investigations of non-linear fracture problems. Here, studies of trabecular bone failure are presented. Such work is of interest due to the impact of bone degradation on the aged. Cracks in trabecular bone are found to be bridged by mineralized collagen fibrils. A multiscale mechanical modeling framework is developed. Nanoscale deformation mechanisms for fibrils are studied by a composite model containing mineral, collagen, and interfaces modeled by cohesive zones. The fibrils response together with the extrafibrillar matrix determines the crack bridging characteristics. Cohesive zone models are used in studies of crack growth in individual trabeculae for monotonic and cyclic loading. Effects of length scales (trabecular thickness and bridging length) in their relation to strength, fatigue, and signaling for bone remodeling are discussed.

Bridged and cohesive crack models for fracture in composite material systems

10123
Mon·11:40·C

Roberta Massabò
University of Genova, Italy

Since the early works of Barenblatt and Dugdale, the cohesive and bridged crack models have been used extensively to model fracture in composite systems where nonlinear mechanisms develop along extended regions of the crack surfaces. In these systems, fracture becomes a large scale bridging problem that cannot be described by LEFM or characterized by a single fracture parameter and characteristic length/time scales control the fracture characteristics and govern the transitions in the response, size scale effects and modes of failure. The two modelling approaches will be recalled and applications to composite materials and systems for civil, naval and aeronautical structures will be presented. Recent results on the problem of multiple dynamic delamination fracture in multilayered plates will be presented and the effects of the interaction between delaminations and of nonlinear crack face mechanisms on energy absorption and damage tolerance will be discussed.

10511
Mon·12:20·C

Modelling strain localization by cohesive/overlapping zones in tension/compression: brittleness size effects and scaling in material properties

Alberto Carpinteri† and Marco Paggi
Politecnico di Torino, Italy†

The present contribution represents a state-of-the-art review of the research work carried out at the Politecnico di Torino during the last two decades on the modelling of strain localization in quasi-brittle and composite materials. Introducing the elementary cohesive/overlapping models in tension/compression, it is possible to get a deeper insight into the ductile-to-brittle transition and into the scaling of the material properties usually detected when testing quasi-brittle material specimens or structures at different size-scales. Special emphasis is also given to the issue of stability of the mechanical response, showing that the brittle behaviour and LEFM critical condition are represented by the occurrence of post-peak softening branches with positive slopes, leading to catastrophic snap-back instabilities under displacement control.

12034
Tue·09:15·C

Cohesive-zone modelling of adhesive joints

Michael Thouless
University of Michigan, USA

Historically, the properties of adhesive joints have been modeled by two different approaches: strength- and energy-based criteria. Cohesive-zone models form a natural and self-consistent approach to bridge these two approaches within a single framework. In systems for which the adherends remain elastic, cohesive-zone models, characterized by an interfacial strength and toughness, can be formed to allow many well-known concepts of interfacial fracture mechanics to evolve. In systems for which the adherends deform in a plastic fashion, cohesive-zone models provide a framework for analysis in a regime that cannot be addressed by fracture mechanics. However, a practical issue is then how to determine, in a relatively simple fashion, rate-dependent cohesive parameters that can be used in mixed-mode applications. This is of particular interest for automotive applications where a methodology for designing adhesive joints for energy-management during crashes needs to be developed.

11212
Tue·10:40·C

Fracture in confined thin films: a discrete dislocation study

Audrey Chng† and William Curtin
Institute of High Performance Computing, Singapore†

The fracture toughness of thin metals film confined between elastic layers is studied using the discrete dislocation (DD) method. Fracture along the metal/substrate interface is permitted through use of a cohesive zone model. The predicted fracture toughness versus film thickness is in good agreement with experimental data on the Cu/TaN/SiO2/Si system. The predicted 0.2%-offset yield stress also agrees with values derived by fitting a continuum plasticity model to the experimental fracture data. Overall, the results show that the DD framework is able to model simultaneous size effects associated with boundary constraints and crack tip fields solely through the evolution of the dislocation structures, and that the DD method is a valuable tool for understanding the complex interplay of dislocation plasticity with small-scale boundary conditions, decohering surfaces, and crack tips, all of which interact to control fracture in thin films and other micro-scale structures.

Length-scale dependency of crack tip fields under mode I loading

11985
Tue·11:00·C

Lars Mikkelsen† and Stergios Goutianos
Technical University of Denmark, Denmark†

Conventional plasticity theories fail to simulate highly localized deformation fields in a realistic way. The size dependency of the deformation fields from the underlying microstructure is not taken into account. Nevertheless, using a gradient dependent plasticity model, a homogeneous continuum model will show such a size dependency. The strain gradient dependent plasticity model used is a reformulated version proposed by Fleck and Hutchinson in 2001. The model is implemented in a finite strain version of a finite element code. The model has been used to investigate the size dependency of the crack tip field in a homogeneous material loaded in pure mode I. For initially blunted crack tips scale effects has been found for material length scales larger than 0.1-1 times the size of the yielding region. In addition, for material length scale larger than 10 times this reference size, it is found that the predictions coincide with a purely elastic material response.

Direct extraction of rate-dependent traction-separations laws for polyurea/steel interfaces

10818
Tue·11:20·C

Kenneth Liechti,† Krishnaswamy Ravi-Chandar and Yong Zhu
University of Texas at Austin, USA†

Polyurea coatings on steel form tough, flexible and chemically resistant surfaces, making them ideal for a variety of applications. An important issue for polyurea coatings in some cases is their adhesion to steel under various loading conditions in aggressive environments. In this paper, adhesion was examined using steel/polyurea/steel sandwich specimens and interfacial fracture mechanics. The mode 1 and mode 2 interfacial fracture behaviors were characterized by two independent traction-separation laws, which were measured directly by recording the J-integral and the end-opening displacements normal and tangential to the steel/polyurea interface. In each case, the traction was initially nonzero, increased with increasing separation, reached its peak value and then decreased with further increasing opening. Strong rate-dependent effects were found for both modes of fracture and were attributed to the interfacial behavior

Micromechanics of elasto-damaging cohesive materials

10921
Tue·11:40·C

Bernhard Pichler† and Luc Dormieux
LMSGC/ENPC/ParisTech and TU Wien, Austria†

To study quasi-static microcracking of brittle materials exhibiting softening behavior, an elasto-damaging cohesive zone model is used in the framework of micromechanics. The model links cohesive tractions to displacement discontinuities by means of an elastic law, whereby the cohesive zone stiffness decreases with increasing displacement discontinuity according to a power law. The essential prerequisite for our analyses are estimates of the cohesive zone size, obtained from applying the theorem of minimum potential energy. These estimates allow (i) for performing a stability analysis of the growth of cohesive zones ahead of stationary (non-propagating) cracks, and (ii) for quantifying energy dissipation associated with mode I propagation of microcracks with fully grown cohesive zones. Model validation is accomplished successfully, by comparing model predictions both with available exact solutions and with results from reliable Finite Element analyses.

A cohesive model coupling friction and adhesion for interfaces and fractures and applications

11327
Tue·12:00·C

Michel Raous,[†] Yann Monerie, Mohamed Karray, Mathieu Schryve and Carole Henninger
Laboratory of Mechanics and Acoustics, CNRS, France[†]

A model coupling adhesion, friction and unilateral contact taking into account viscosity effects is given. Damage is considered by using the notion of intensity of adhesion first introduced by M. Frémond. The variational formulation is given as variational inequalities for quasistatic problems. The dynamics is solved with the Non Smooth Contact Dynamics method of Moreau-Jean. This model is used to simulate both debonding interfaces and ductile crack propagation. Applications are first presented in composite mechanics (interaction of cracks and fiber/matrix interfaces), civil engineering (steel/concrete interface for reinforced concrete). An extension to healing adhesion is presented for rubber/glass contact. Results on an undergoing research related to earthquake analysis is presented where this behavior law is used to simulate the contact between tectonic plates.

General method for micromechanical based derivation of separation laws

11328
Tue·12:20·C

Ingo Scheider
GKSS Research Centre, Germany

A general method is proposed for the derivation of traction-separation laws for cohesive models, which is based on numerical simulations of a representative volume element with heterogeneous microstructure. The failure of this microstructure may consist of various damage mechanisms, which must be included in the simulation. From the mesoscopic response of the micromechanical model the complete traction-separation law is extracted, which is then in general dependent on the applied triaxility and other field quantities like loading rate, etc. The approach is applied to a short fibre reinforced metal-matrix composite, which is modelled by a 3D RVE containing several fibres in different directions.

Simulation of delamination growth under high-cycle fatigue using cohezive-zone models

12185
Tue·16:00·C

Albert Turon,[†] Pedro Camanho and Josep Costa
University of Girona, Spain[†]

A cohesive zone model is proposed for the simulation of delamination growth in polymer-based composite materials subjected to high-cycle fatigue loading. The basis for the formulation of the model is an interfacial constitutive law that relates the evolution of the damage variable, d, with the crack growth rate, dA/dN. The damage state is a function of the loading conditions (mode ratio, load ratio, applied energy release rate), and of the experimentally-determined crack growth rates for the particular type of composite material used. The cohesive zone model is implemented in ABAQUS finite element code as a user-defined element and it used in the simulation of carbon-epoxy test specimens cyclically loaded in mode I, mode II and mixed-mode I and II. The accuracy of the model is assessed by comparing the numerical predictions with experimental data.

Cohesive model and experimental analysis of PMMA at high rate

11061
Tue·16:20·C

Rafael Estevez,† Christian Olagnon, Diego Scriba, Nesrine Saad-Gouider and Henri Sautereau
Université Lyon, France†

We present a numerical and experimental study of glassy polymer fracture at high rates. An elastic-viscoplastic description is used for the bulk with softening upon yielding followed by hardening. Failure by crazing is modelled with a viscoplastic cohesive zone that mimics initiation, thickening and fibrils breakdown at a craze critical opening resulting in the nucleation of a crack locally. Based on a realistic calibrated parameters for PMMA at low rates, we compare predictions to experiments for which the time to failure is about 0.1-1 millisecond. A coupled thermomechanical analysis is carried out with account for possible heat generation of the bulk viscoplasticity and from the craze fibrillation process. It is shown that crazing is the major heat source and that the craze critical opening for failure needs to be temperature dependent to capture the brittle to ductile transition observed at high loading rates.

Element-free Galerkin modelling of cohesive crack propagation in composite laminates

12134
Tue·16:40·C

Brian Falzon,† Irene Guiamatsia and Glyn Davies
Monash University, Australia†

Predicting failure in realistic aircraft components, with geometrical discontinuities, demands greater flexibility in the handling of topology changes when it is required to follow the propagation of damage until ultimate failure. Meshless methods are established in the analysis of crack propagation in concrete structures. The simplicity of node generation and adaptivity operations is key to the numerical simulation of the propagation process, especially for composite laminates which exhibit a delamination process zone size of the order of a millimetre. The Element Free Galerkin method is favored in this work, for its robustness and consistency amply documented in the literature. Excellent results have been obtained for a simple DCB specimen using the VCCT technique for crack advancement. Ongoing work is focused on the formulation of the cohesive region enclosing a developing crack, in order to simulate multiple crack fronts evolving simultaneously within a continuum damage mechanics framework.

On measurement and modeling of interfacial behaviors between thin films and substrates using peel test

11330
Tue·17:00·C

Yueguang Wei† and Haifeng Zhao
Chinese Academy of Sciences, China†

Two types of peeling experiments are performed in the present research. One is for the Al film/Al_2O_3 substrate system with an adhesive layer between the film and the substrate. The other one is for the Cu film/Al_2O_3 substrate system without adhesive layer, and the Cu films are electroplated onto the Al_2O_3 substrates. The relationships between energy release rate, film thickness and adhesive layer thickness are measured during the steady-state peeling. Using the experimental results, several analytical criteria based on the bending model and on the two-dimensional finite element analysis model are critically assessed. We find that the cohesive zone criterion based on the beam bend model is suitable for a weak interface strength case and it describes a macroscale fracture process zone case, while the two-dimensional finite element model is effective to both the strong interface and weak interface, and it describes a small-scale fracture process zone case.

A mixed-mode constitutive damage model for multi-scale fracture analysis of composite structures

11279
Tue·17:20·C

Anders Hansen† and Erik Lund
Aalborg University, Denmark†

A generalized constitutive damage model of an interface finite element is proposed on basis of a multi-scale cohesive zone model taking into account small and large scale fracture mechanisms in fiber reinforced materials. An irreversible damage parameter is established in terms of piecewise linear traction-separation relations such that the energy dissipation becomes a function of relative displacements. Model parameters are determined experimentally from measured R-curves obtained by analytical J-integral calculations. The constitutive model is verified experimentally and numerical investigations of model parameters have been performed. Initiation and propagation of interlaminar fracture exhibiting large scale fiber bridging is studied experimentally and numerically on structural-size beams and plates under mixed mode loading. Numerical and experimental results are in fine agreement illustrating the general applicability of the proposed multi-scale constitutive damage model.

Influence of softening function on concrete fracture using cohesive crack model

11023
Thu·14:35·5

Shailendra Kumar† and Sudhirkumar Barai
Indian Institute of Technology, Kharagpur, India†

The cohesive crack model based on an enhanced algorithm for three-point bending test geometry of notched concrete beams is developed. Seven widely used softening functions are incorporated in the program and results of cohesive crack model for concrete beams are analyzed and compared. The input parameters in the model are used from a recently published experimental result. It is found that the difference between maximum and minimum peak loads predicted using different softening functions (except linear) is less than 8% for laboratory size test specimens. The peak load predicted using linear softening function is approximately 10% more than with the other softening functions (bilinear curves, exponential, nonlinear). The peak load is not affected by changing the values of the kink point (stress ratio) in bilinear softening curves whereas this effect is pronounced in post-peak response of the beams.

A slip band based cohesive zone model for simulations of fatigue crack growth at sub-micron level

11291
Thu·14:40·5

Xiaobo Yu,† Callum Wright and Manfred Heller
Defence Science and Technology Organisation, Australia†

This study is a part of a broad investigation to achieve a more fundamental understanding of fatigue crack growth mechanisms under variable amplitude loads. It was motivated by recent experimental observations of AA7051-T7451 fatigue tests where periodic underloads resulted in crack path deviations and bifurcations forming fissure and ridge patterns at a sub-micron level. A 2D cohesive zone model is proposed based on assumptions that: a) plasticity is due to slip deformations along pre-defined directions; b) a minimum space is allowed between parallel slip bands; c) hardening is influenced by sliding along the current and latent slip systems, as well as sliding gradients; and d) a crack propagation is to occur when the resolved normal tension reached material strength that locally degraded due to accumulated damage under cyclic slip. The cohesive zone model is implemented in ABAQUS using UEL and UEXTERNALDB user subroutines. Case studies in line with experimental trials are proposed.

Cohesive zone model for intergranular stress corrosion cracking in ceramics

11558
Thu·14:45·5

Marc de la Osa,† Rafael Estevez, Christian Olagnon, Jérôme Chevalier, Christophe Tallaron and Lionel Vignoud
Université de Lyon, France†

Ceramic polycrystals are prone to Slow Crack Growth (SCG) that is also environmentally assisted, similarly to what is observed for glasses. The kinetics of fracture are known to be dependent on the load level, the temperature and also on the relative humidity (RH). However, evidence is available on the influence of the microstructure on the SCG rate with an increase in the crack velocity with decreasing the grain size. This latter observation motivates a cohesive zone formulation of the -intergranular- failure process. The methodology accounts for an intrinsic opening that governs the length of the cohesive zone and ultimately allows the investigation of grain size effects. A rate and temperature dependent cohesive zone is proposed to mimic the reaction-rupture mechanism. We indicate how the parameters involved in the description can be determined and present 2D simulations of intergranular fractures for diverse grain sizes.

Solution strategy for large three-dimensional composite structures with geometric and material instability under mixed-mode loading

11943
Thu·14:50·5

Lars Overgaard,† Pedro Camanho and Erik Lund
Aalborg University, Denmark†

The objective of this work is to do structural analysis of large three-dimensional laminated composite structures with geometric and interlaminar material instability under mixed-mode loading. To reach this objective a cohesive element able to predict delamination propagation under mixed-mode loading and a layered continuum-based solid-shell element is used. The constitutive softening models of cohesive elements cause severe solution difficulties. Thus an efficient and robust solution strategy for the simulation of large three-dimensional structures is proposed and Implemented. The applied numerical methods are demonstrated by studies of fracture mechanics test specimens. Finally, it is shown in an engineering case study of a generic laminated composite wind turbine blade that the proposed methods can predict the structural behavior of large three-dimensional structures based on non-linear fracture mechanics in a geometrically non-linear framework.

MS02 ::
Multi-component materials, modelling on different scales

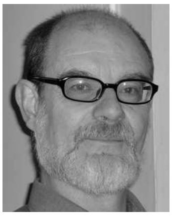
Chairs: Henryk Petryk (Poland) and Francis Rose (Australia)

Mon	11:00–13:00	Hall D	Lectures
Tue	10:40–12:40	Hall D	Lectures
Tue	14:35–14:55	Room 2	Seminars
Tue	16:00–17:40	Hall D	Lectures
Wed	10:40–13:00	Hall D	Lectures

Multi-scale analysis of polycristalline metals and composites

11332
Mon·11:00·D

Jean-Louis Chaboche
ONERA, Châtillon, France



Some of the available multi-scale modelling methods are reviewed for the inelastic analysis of polycrystalline metals and metal matrix composites, in the context of component integrated analyses. They include numerical finite element based periodic homogenisation methods and mean-field based approaches together with several of their variants. Difficulties associated with an adequate treatment for material non-linearities in mean-field approaches will be discussed. Typical examples are chosen in order to illustrate these approaches, including examples of three scale methods.

Modelling multi-scale damage evolution in composite materials

11727
Mon·11:40·D

Brian Cox
Teledyne Scientific, USA

Recent successes towards developing high fidelity simulations of damage evolution in engineering structural composites will be presented. Illustrative cases include conventional laminates and laminates incorporating through-thickness fibers, which enhance delamination crack resistance. These examples encourage the expectation that simulations may soon replace many (but never all) experiments in the design of composite structures. The top-down view of damage modeling relies on discovering all the mechanisms of damage that have an observable effect on the outcome of an engineering test. This stipulation leads to the association of a length scale with any mechanism (the minimum volume that must be affected by the mechanism for its consequences to be macroscopically observable). The length scale will appear, at least implicitly, in the formulation of a micromechanical model of the mechanism and also in the definition of an appropriate mesh size.

Instabilities across the scales

12133
Mon·12:20·D

Hans Muhlhaus† and Louis Moresi
The University of Queensland, Australia†

A significant theme of recent research activities in science and engineering revolves around the modelling and numerical simulation of instabilities. Instabilities appear in various ways and at different scales of observation. They reflect a change in the fundamental behaviour of physical systems and often act as a precursor to failure. In my talk I will highlight analogies regarding the modelling of instabilities at different scales of observation (planetary to engineering scale), and present a brief review of the current state-of-the-art on computational procedures appropriate for the numerical simulation of instabilities across a wide range of scales.

Chemically driven inelastic deformation in materials with non-ideal sources and sinks for vacancies

10629
Tue·10:40·D

Franz Fischer† and Jiri Svoboda
Montanuniversität Leoben, Austria†

Diffusion in multi-component crystalline systems can be characterized by the vacancy mechanism for slowly diffusing substitutional components leading to a constraint amongst fluxes of vacancies and substitutional components, non-ideal sources and sinks for vacancies causing their non-uniform generation/annihilation accompanied by dissipation, and quick diffusion of interstitial components changing the lattice constants due to their concentrations. The last two mechanisms are responsible for local swelling and shrinkage. Both diffusion and vacancy generation/annihilation are supposed to be proportional to chemical and mechanical driving forces. Evolution equations are derived from the principle of maximum dissipation. Diffusion and vacancy generation/annihilation in isotropic materials are independent processes. Two relevant kinetic coefficients, the bulk and shear viscosities, can be introduced. The inelastic deformation state is demonstrated on a bamboo-structured wire.

An analysis of textile reinforced concrete structures on the micro, meso and macro scale

11164
Tue·11:00·D

Bernd Zastrau,† Ingolf Lepenies and Mike Richter
Technische Universität Dresden, Germany†

Textile reinforced concrete (TRC) is a composite of rovings (multi filament yarns) and fine grained concrete which is used in civil engineering to fabricate new structural elements and to strengthen existing constructions. The presentation deals with structural models of the macro-scale, using the detailed information of the micro- and mesoscopic models to simulate the behavior of typical structural members made of reinforced concrete. Due to the textile reinforcement in TRC the crack opening displacements are very small. This leads to the major influence of the post cracking behavior of concrete on the overall response of the structural member. In the case of a steel and textile reinforced concrete plate the simulated crack width of the meso-model is used to capture this effect within the framework of a multi scale analysis.

Multiscale computing of CNTS fracture based on quasicontinuum/density functional theory hybridization

11753
Tue·11:20·D

Jong Park,† Ki-Jeong Kong, Hyun Chang, Chan Park and Seyoung Im
Korean Advanced Institute of Science and Technology, South Korea†

An effective multiscale computing scheme based on QC/DFT (quasicontinuum/density functional theory) is applied for simulation of CNTs (Carbon Nano Tubes) fracture under tension. Firstly an adaptive multiscale simulation of deformations of curved crystalline structures such as CNTs, based on quasicontinuum approach, is established to look into fully nonlocal behavior of CNTs. Next the multiscale computing based on QC/DFT hybridization is devised and applied for simulation of CNTs fracture. Considered are single walled CNTs, with various types of vacancy or dangling bonds, subjected to uniaxial tension. The theoretical strength of CNTs is computed based on QC/DFT coupling scheme. It is found that this multiscale computing greatly improves the prediction of the failure strains of CNTs in comparison to molecular mechanics or quasicontinuum method.

Micromechanics of deformation of persulfonated polytetrafluoroethylene (Nafion) proton exchange membranes

11657
Tue·11:40·D

Meredith Silberstein† and Mary Boyce
Massachusetts Institute of Technology, USA†

Fuel cells enable direct chemical to electrical conversion of fuel to useable energy, providing an efficient and clean process. Proton Exchange Membrane Fuel Cells (PEMFC), in which protons from hydrogen cross a membrane to react with oxygen producing electricity, are the preferred fuel cells for power conversion. Nafion, a phase separated perfluorosulfonated ionomer, is the current benchmark membrane but still exhibits limited lifetime due to stress encountered during cyclic hygro-thermal loading. Here, the micromechanics of Nafion deformation are examined through in-situ small and wide angle x-ray scattering during tensile testing and cyclic mechanical evaluation over a range in temperature and hydration. A micromechanically inspired constitutive model for Nafion is developed based on uniaxial tensile and x-ray diffraction data. This model is shown to capture the rate, temperature, and hydration dependent non-linear loading and unloading behaviour.

Constitutive description of plastic strain induced phenomena at cryogenic temperatures

10404
Tue·12:00·D

Blazej Skoczen
Cracow University of Technology, Poland

FCC metals and alloys undergo at cryogenic temperatures three phenomena: discontinuous plastic flow, plastic strain induced phase transformation and evolution of micro-damage. As all of them lead to irreversible degradation of lattice a combined constitutive description, including thermodynamic background, is fundamental for low temperature applications. Discontinuous plastic flow is described by the mechanism of catastrophic failure of Lomer-Cottrell locks under the stress fields related to accumulating edge dislocations. The strain hardening model, corresponding to fcc-bcc phase transformation, is based on micro-mechanics and on the Hill concept (tangent stiffness of two-phase continuum) including the Mori-Tanaka homogenization. The micro-damage description results from a generalization of the classical isotropic ductile damage concept to anisotropic model. The constitutive model is based on a suitable experimental background.

Stresses in topologically interlocking structures: two scale approach

10134
Tue·12:20·D

Arcady Dyskin,† Yuri Estrin, Elena Pasternak and David Yong
University of Western Australia, Australia†

Topological interlocking structures are built from blocks which are not connected to each other and hence have a capacity to move independently (within the geometrical constraints imposed by the structure). This property is useful as it provides high energy absorption of both impact and vibrations. The structural integrity is achieved by external constraint. The actions of constraint and the external load create stress distribution which is large-scale relative to the block size. The large-scale compression can generate local tensile stresses in blocks due to the non-planar nature of the contact surfaces. The tensile stresses have to be controlled as they can produce cracks within the blocks and the subsequent block failure. Another effect of the curved contact surfaces in the presence of friction is the developing of stress oscillations in some parts of the contact. The mechanism of the oscillations might be similar to the oscillating singularity in rigid punch without sliding.

Nonlinear dynamic response and self-sensing of functionally graded piezoelectric transducers

10429
Tue·14:35·2

Fumio Narita,† Jun Nakagawa and Yasuhide Shindo
Tohoku University, Japan†

We study theoretically and experimentally the nonlinear dynamic response and self-sensing behavior of functionally graded piezoelectric transducers under alternating current electric fields. The contribution of domain wall motion to the elastic compliance, piezoelectric coefficient and dielectric permittivity in soft lead zirconate titanate layers is evaluated, and a nonlinear finite element analysis is performed to discuss the effects of the amplitude and frequency of input voltage, number of layers and property gradation on the sound pressure, output voltage, and internal stresses and electric field for clamped-clamped functionally graded piezoelectric transducers. In order to confirm the numerical results, bending tests on the transducers are conducted, and the sound pressure and output voltage are measured. It is found that the stress gap near the interface becomes low as the piezoelectric properties increase toward the mid-plane of the bimorphs.

Evolution of the bonding mechanism of ZnO under isotropic compression: a first-principles study

11214
Tue·14:40·2

Jinbin Wang,† Gongcheng Zhou, Lizhong Sun and Yichun Zhou
Xiangtan University, China†

The evolution of the electronic structure and the bonding mechanism of ZnO under isotropic pressure have been studied by using the full-potential linear augmented plane wave method within the density-functional theory based on LDA+U exchange correlation potential. We used the theory of atoms in molecules method to analyze the change of the charge transfer and the bonding strength under isotropic pressure. The results of the theoretical analysis show that under high pressure the charge density along the Zn-O bond increases. And with the pressure enlarging, the charge transfer between Zn and O atomic basins enlarges linearly. The bonding strength and the ionicity of Zn-O bond also increase due to the pressure. The linear evolution process of the bonding mechanism under pressure was shown clearly in the present paper.

Response of solids under electrical, magnetic, and mechanical loads

11292
Tue·14:45·2

Su Hao,† Qian Wang, Leon Keer and John Ketterson
Northwestern University, USA†

When an engineering system is under mechanical, electrical, and magnetic loads, an issue is to evaluate its mechanical stability and endurance. This is because accurate computation of magnetic field is still a challenge; on the other hand, materials discontinuities such as grain boundaries, inclusions, and microcracks, introduce second phase that can be dielectric or with significant differences in conductivities. Electric-current induces magnetic field and enhanced Lorentz' force; skin effect and magnetic wave may also present. Theoretical analysis and numerical computations have been performed. Close-formed solutions of Maxwell's equations, equilibrium equation, and heat conducting equation for some simplified cases have been obtained. Multi-physics-based material constants have also been obtained to characterize the response of a solid under the above-mentioned complicate loads, providing quantitative information for materials selection and system design.

Implicit constitutive modeling based on the energy principle

11427
Tue·14:50·2

Hou Man,† Tomonari Furukawa and David Kellermann
University of New South Wales, Australia†

This paper presents a method of implicit constitutive modeling based on the energy principle. The proposed method has the ability to produce consistent resultant models for various materials by simultaneously considering multi-directional responses on a single specimen. The number of specimens used in the model development process can also be reduced significantly since information, such as the potential energy, at each load step is fully utilized. Neural networks are applied as the implicit techniques to capture the strain-stress relationship with the reformulated training function in terms of the strain energy and the external works. This method is, therefore, able to model both linear and nonlinear constitutive behavior. A selected composite laminate as well as a nonlinear material have been used for the performance validation. The results on both resultant models emphasize that the proposed method can be broadly applied to model various materials with high effectiveness achieved.

Crystal microstructure design of piezoelectric materials by multiscale finite element analysis

11444
Tue·16:00·D

Yasutomo Uetsuji
Osaka Institute of Technology, Japan

Piezoelectric materials have a large possibility to exhibit higher performance in a macroscopic scale by design of crystal morphology in a microscopic scale. In this paper, a multi-scale finite element method based on homogenization theory is employed to optimize the microstructure of polycrystalline piezoelectric materials so as to maximize the homogenized macrostructural piezoelectric response. This analysis reveals that two specific microstructures, layered or alternating [111]-oriented structures, result in a piezoelectric response that exceeds that of the single crystal. The layered structure consists of ordered 120°-rotated layers maximizing d_{333}, while the alternating structure consists of adjacent grains rotated by 180° in three dimensions optimizing d_{311}. These heterogeneous structures maximize the internal strain in polycrystalline aggregates by optimizing electrical and mechanical effects.

Constitutive model of discontinuous plastic flow at cryogenic temperatures

11188
Tue·16:20·D

Jan Bielski† and Blazej Skoczen
Cracow University of Technology, Poland†

Discontinuous (serrated) yielding is characteristic both of low and high stacking fault energy materials strained at very low temperatures. It represents oscillatory mode of plastic deformation. Serrated yielding is described by the mechanism of local catastrophic failure of Lomer-Cottrell locks under the stress fields produced by the accumulation of edge dislocations. Failure of LC locks leads to massive motion of released dislocations accompanied by rapid load drop and stress relaxation. The process has been subdivided into four stages. The main function that reflects the readiness of the lattice with respect to discontinuous plastic flow is the cumulative volume of dislocation groups per unit volume of lattice. Kinetics of evolution of the volume fraction of dislocation groups has been postulated at the mesoscopic level and the relevant constitutive model has been derived. Dislocation groups production rate has been identified on the experimental basis.

Transition between models in multiscale simulations: continuum and granular models

11695
Tue·16:40·D

Jagan Padbidri† and Sinisa Mesarovic
Washington State University, USA†

We consider two-scale problems: the fine-scale model and the coarse-scale continuum. The key problem here is passing information of the coarse-scale fields to the fine scale cell, solved using Minimal Boundary Conditions (MBC). We summarize the application to fine-scale continuum models to fine-scale discrete models with local interactions—granular materials. The key to this application is the equivalent representation of kinematics of granular flow using the Delaunay network.

Optimization and identification of multi-component materials in modelling on different scales

11881
Tue·17:00·D

Tadeusz Burczynski† and Waclaw Kus
Silesian University of Technology, Poland†

The paper deals some aspects of optimization and identification of multi-component materials in modelling on different scales. The transition from macro to micro-scales is performed by the computational homogenization. On the micro-scale level a composite as the multi-component microstructure, made from two or more different materials, is considered. Material and geometrical parameters of micro-component microstructure are selected as design variables. Optimization and identification problems are performed by evolutionary algorithms. The goal of the optimization is to obtain the composite which gives the best performance of the structure on the macro-scale for a given objective function. The identification is performed to obtain material properties for fiber and matrix materials or their shapes on the basis of measured displacements at sensor points of the macrostructure. Numerical tests of designing optimal multi-component materials are presented.

Propagating modes of nano-scale periodic layers of solid-fluid composites

11071
Tue·17:20·D

Chien-Cheng Chang† and Ying-Hong Liu
Academia Sinica, Taiwan†

The study aims to investigate propagating modes of nano-scale periodic layers of solid-fluid composites with or without damping in the fluid phase. A three-scale homogenization analysis is developed to derive the effective group velocities in analytical forms for the shear-vertical (SV) as well as longitudinal-shear horizontal (P-SH) waves. It is found that propagating modes, i.e. modes with real group velocities may be supported if the viscosity of fluid phase is frequency-dependent. A criterion for the propagating modes is established between the composite medium constants as well as the filling ratio of the fluid phase. The critical filling ratios at which an evanescent mode would change to a propagating mode are given for various solid-water systems.

A multiscale model for the sintering of air-plasma sprayed thermal barrier coatings

10568
Wed·10:40·D

Alan Cocks† and Norman Fleck
University of Oxford, UK†

Air-plasma sprayed thermal barrier coatings contain intersplat cracks in the as deposited condition. These cracks enhance thermal insulation and promote strain tolerance. In service, the cracks can heal due to the sintering at contacting asperities across the faces of the cracks. A multiscale model is presented which takes into account the coupling between continuum elastic and creep deformation of the coating and sintering due to interface diffusion at the scale of the asperities. The resulting constitutive model is used to evaluate the evolution of microstructure and macroscopic elastic properties of a coating deposited on a thick substrate.

Multi-scale modeling of stress-induced microstructures in shape memory alloys

10509
Wed·11:00·D

Henryk Petryk† and Stanislaw Stupkiewicz
Institute of Fundamental Technological Research, Poland†

A novel multi-scale approach to the modeling of pseudoelastic behavior of polycrystalline shape memory alloys is presented. The approach is based on step-by-step minimization of the incremental energy supply in combination with sequential micro-macro transition in a three-dimensional setting. The intrinsic dissipation related to creation, propagation and annihilation of phase interfaces in grains is included along with the interfacial energy and size effects. A calculation scheme is proposed that provides a multi-scale transition from atomic lattice rearrangements up to the macroscopic behavior of a polycrystal. With an evolving rank-two laminate as a basis, two further intermediate levels, of sub-domains and of bi-crystals, are introduced. Overall stress-strain diagrams with hysteresis loops are determined for a polycrystalline aggregate with a locally evolving microstructure under proportional and non-proportional loadings and compared to the experimental data.

Parametric study of strain hardening behaviour of glassy polymers using molecular simulations

12062
Wed·11:20·D

Sumit Basu† and Dhiraj Mahajan
Indian Institute of Technology, Kanpur, India†

The stress needed to deform a polymer glass increases as the strain rises. While numerical models have been successful in fitting experimental data, fundamental clarity of the parameters used is still lacking. Most theories of strain hardening are based on rubber elasticity theory. These models assume that polymer glasses behave like cross-linked rubber, with the number of monomer between cross-links equal to the entanglement length. While stress-strain curves for a wide variety of glassy polymers can be fitted, but the fit parameters are not consistent with the microscopic picture underlying these models. To this end, molecular simulations of generic glassy polymers are done to find their realistic parameters. These parameters are then used as fitting parameters for stress-strain behavior during deformation under NEMD simulations. In spite of entanglement density, strong correlation between Kuhn length segment density with fitting parameter in entropic network model is found.

Ductile damage evolution in two-phase metallic materials applied at cryogenic temperatures.

10717
Wed·11:40·D

Halina Egner† and Blazej Skoczen
Cracow University of Technology, Poland†

At cryogenic temperatures three principal phenomena are detected in metallic materials: serrated yielding, damage evolution and fcc-bcc phase transformation. The mechanism of damage in austenitic lattice is related to formation of plastic strain fields, while in martensite it exhibits rather brittle character. In the proposed constitutive model ductile damage rate tensor depends on the accumulated plastic strain rate as well as on the strain tensor. Strain equivalence principle is adopted to define the effective stress as well as the kinematic and isotropic strain hardening variables in the equation of the von Mises-type yield surface. The parameters of constitutive model have been experimentally identified at CERN. The constitutive model was implemented into ABAQUS finite element code via user defined subroutine VUMAT. Numerical simulation of damage evolution in thin axisymmetric shells was performed and compared to experimental observations.

Multiscale models for multi-component structural energetic materials

11630
Wed·12:00·D

Sathya Hanagud,† Rusi Zaharieva and Xia Lu
Georgia Institute of Technology, USA†

Usual multi-component materials consist of composite materials, granular materials, biomaterials and geo materials. This paper describes a new class of multi- component materials that are based on intermetallics. An example is a composite of Ni, Al, carbon nano tube structural reinforcements, with both strength and energetic characteristics. They are synthesized and modeled. The models are developed from atomistic scales (ab initio methods) by using density functional theory and the constitutive equations are bridged to continuum scales, to study impact problems. Failures are characterized by abintio molecular dynamics. Applications of such materials involve loading of impact and penetration into hard targets. The specific multi-component material is a mixture and not an alloy. Currently, first principle theories for disordered materials do not consider mixtures. A supercells approach, based on virtual crystal approximations is used. Then, the question of failure criteria is addressed

Inverse modelling to identify fibre hygroexpansion coefficient from experimental results of wood-fibre composites swelling

11458
Wed·12:20·D

Karin Almgren,[†] Fredrik Berthold, Janis Varna and Kristofer Gamstedt
STFI-Packforsk AB, Sweden[†]

Increased environmental awareness has contributed to the research and development of environmentally friendly wood-fibre composites. The absorption of moisture is however a severe problem preventing wood fibres from reaching their full potential as structural material. It is therefore crucial to the development that the dimensional stability is improved. Chemical modifications can be used to reduce swelling of the wood fibres, but evaluation of the modifications is difficult since the miniscule dimensions of the fibres make single fibre measurements cumbersome. Inverse micromechanical modelling is therefore a convenient tool in the determination of fibre properties, which can be used to rank different fibre treatments in terms of their contribution to a dimensionally stable composite material. Back calculation from Hashin's micromechanical models and laminate analogy was successfully used to determine transverse coefficient of hygroexpansion of modified and untreated reference fibres.

Constitutive model of plastic strain induced FCC–BCC phase transformation at cryogenic temperatures

11230
Wed·12:40·D

Adam Wroblewski[†] and Blazej Skoczen
Cracow University of Technology, Poland[†]

During the plastic strain induced fcc-bcc phase transformation that occurs in low stacking fault energy materials at cryogenic temperatures the austenite is transformed into martensite. Constitutive model used to describe the phase transformation involves strain hardening where two effects play fundamental role: interaction of dislocations with martensite inclusions and increase of material tangent stiffness due to mixture of harder and softer variants. Interaction of dislocations with inclusions is reflected by the hardening modulus that depends on the volume fraction of martensite. Tangent stiffness of two-phase continuum is computed via the Mori-Tanaka homogenization scheme, taking into account local tangent stiffness moduli of both variants. The material model is suitable for wide range of temperatures, however, best results are obtained for very low temperatures, where a linear form of kinetic law of phase transformation is valid.

MS03 :: Mechatronics

Chairs: Karl Hedrick (USA) and Heinz Ulbrich (Germany)

Mon	11:00–13:00	Room 1	Lectures
Tue	15:00–15:15	Room 2	Seminars

10329
Mon·11:00·1

Trajectory planning for linearly-actuated elastic robots using flatness based control theory

Mathias Bachmayer† and Heinz Ulbrich
Technische Universität München, Germany†

Elasticities in industrial machinery have become more and more important for control strategy design. Especially since achieving higher machine dynamics at constant or even better precision and energetic efficiency has become essential for the manufacturer's competition success. An analytical trajectory planning strategy for elastic robots with linear actuators will be presented to compute feed forward control trajectories for positioning linearly actuated Robots like rack feeders, x-y plotters or placement machines without leaving any vibrations after positioning has been finished. The approach is based on the physics of Euler–Bernoulli beams and enables real time computation of ring time free fast positioning, can be integrated into adaptive control strategies, saves time and leads to very robust solutions.

10756
Mon·11:20·1

Design and control of a novel type hybrid micromanipulator with piezoelectic actuators and vision feedback system

Daniel Prusak† and Tadeusz Uhl
AGH University of Science and Technology, Poland†

In recent years, micro- and nano- robotics have become subjects of intensive scientific research as well as gained an increasing attention from industry (including, inter alia, medicine, biotechnology, fiber optics and astronomy). The current paper confers the project of a three-arm parallel hybrid micromanipulator with 3 degrees of freedom (3DOF) and 6 piezoelectric actuators (3 piezoelectric stack actuators and 3 piezoelectric resonant actuators), designed as a construction linking classic bearing rotary joints and flexible joints (flexures). Basic construction principles, micromanipulator parameters and mathematical equations of the inverse kinematics of the micromanipulator are described in this. The article also presents the control system of the manipulator, which is based on the fast prototyping real-time computer dSPACE with vision feedback control, the latter built based on optical system LEICA and a PC computer to image processing.

11343
Mon·11:40·1

Classical mechanics and electromagnetism: a covariant view

Markus Schöberl† and Kurt Schlacher
Johannes Kepler University, Austria†

In this contribution we present non-relativistic particle mechanics incorporating the Lorentz force induced by the electromagnetic two form in a covariant description based on differential geometric methods. To derive the geodesics of a mass particle a linear connection which splits an appropriate vertical bundle can be used together with an induced covariant derivative. The linear connection can be extended to an affine one, to include the effects of electromagnetism. This results in a covariant description of time variant mechanics including the Lorentz force. Forthcoming work is devoted to a generalization of this to the case of a continuum, which may lead to a coordinate free formulation in magnetohydrodynamics, for example.

Friction discs: torsional slip control and radial dynamics **11806** Mon·12:00·1

Alexander Fidlin
LuK GmbH & Co. oHG, Germany

The radial dynamics of friction discs under slip control is discussed in the present work. It is a modern and practically important way to suppress torsion vibrations in automotive transmissions. Two types of motion are of particular interest: self centering of the friction disc at low rotation speeds and strong vibrations with increasing radial displacements and intensive slip between the discs at high speeds. Although the equilibrium corresponding the self centering always remains stable, its attraction area in phase space shrinks in overcritical domain. The last phenomenon is even amplified by usual control algorithms. The result is unacceptable wear of the friction discs. One of the important ways to solve the described technical problem is to apply a special control strategy limiting the slip control to a certain range of rotation speeds and to enforce sticking at higher rotation speeds, where the torsion vibrations can be isolated by conventional springs and mass dampers.

Adaptive LQ controller for position control of machine tool axis **10993** Mon·12:20·1

Petr Strakos,† Michael Valasek and Josef Bohm
Czech Technical University, Prague, Czech Republic†

A typical procedure when a new machine tool is created is tuning up of the axis feed drive parameters. As traditional concept of axis control the cascade control is used. Tuning of such a controller can be time consuming when trying to find best values and even more classical cascade control assures good control process only under unchanging circumstances. In situations where conditions are changing during machining process, like apparent difference in workpiece mass etc., usage of an adaptive controller is needed. The paper deals with the usage of an adaptive LQ controller suitable for machine tool axis control. By means of simulation, control of a table position driven by a ball screw is analyzed and compared with different types of control approaches, specifically with classical cascade control and state-feedback control. Comparison is based on performing several tests in time domain, while linear machine tool model is extended via non-linearities of friction and input saturation.

New active mounting of machine tool feed drives **11380** Mon·12:40·1

Jiri Sveda,† Michael Valasek and Zbynek Sika
Czech Technical University in Prague, Czech Republic†

Contemporary machine tools are mainly equipped with the motion axis drives that are fixed-mounted on the machine body. Force strokes are directly transmitted to the machine structure during the operation and natural frequencies of the structure are exited. It means that dynamic properties of the machine tool feed drive are restricted. Partial solution could be suspended motor, where the motor is connected with the machine body by a spring and a damper. This paper deals with the proposal of a new conception, in which the feed drive is connected with the machine tool by an active element. We can decrease the force excitation of the body frame by intelligent control of the active element and improve the achievable dynamic parameters. The feed drive motor is mounted on another motor and therefore this concept is called 'motor on motor'.

Representation of hysteresis in discrete electro-magneto-mechanical systems

10682
Tue·15:00·2

Andreas Mueller
Institut of Mechatronics, Germany

One crucial point in the modeling of Electro-Magneto-Mechanical Systems (EMMS) is the representation of hysteresis in ferromagnetic and ferroelectric components. The motion equations of electric and magnetic networks are formulated in terms of electric charges and magnetic fluxes, constituting the generalized coordinates. Therefore, the hysteresis model must be formulated in terms of these coordinates. In this paper a model for hysteresis in magnetic and electric components is presented that is expressed in terms of generalized coordinates of the EMMS. It builds upon the well-known Jiles-Atherton hysteresis model. The Lagrangian motion equations, governing the EMMS dynamics, are derived from energetic state functions. In this way non-linear interactions are correctly taken into account. Furthermore, EMMS can so be considered as controlled Euler-Lagrange systems, and the machinery from non-linear control can be applied to the model-based control of EMMS, such passivity-based control.

Analysis of with lower limb orthosis at sit to stand state

10777
Tue·15:05·2

Dein Shaw,† Chi Huang and Li Huang
National Tsing Hua University, Taiwan†

Lower limb orthosis can be used to assist human to decrease the moment acting on the knee at sit to stand state. In this study, the kinetics motion path of hip and knee joint of healthy subjects using design flexible component structure are investigate. The design of the flexible joint was according to the kinetics path of the relative tibia of femur and the force of the air muscle. And then, measurement of knee angle and reaction force of foot calculated that moment of segment at lower limb. Form to calculate knee moment result to analysis assist effect on lower limb.

Deformation and fracture behavior of ceramic-polymer ferroelectric nanocomposite film under uniaxial tension

11692
Tue·15:10·2

Fei Fang,† Wang Zhe, Zhang Mingzhi and Yang Wei
Tsinghua University, China†

Ferroelectric polymer based 0-3 composite films are very attractive for applications such as capacitors and electric energy storage devices. In this paper, deformation and fracture behavior under uniaxial tension is characterized for $BaTiO_3$/P(VDF-TrFE) ferroelectric nanocomposite film prepared by solution casting and then annealing. Compared with the pure P(VDF-TrFE) copolymer film, the composite film shows an enhanced ductility while a reduced fracture strength. SEM observation and XRD analysis demonstrate that the addition of $BaTiO_3$ powders into the copolymer matrix inhibits the growth of the crystallite size and results in a lower crystallinity than that for the pure copolymer film, leading to the observed stress-strain behavior.

MS04 :: Mechanics of colloidal systems

Chairs: Dominique Langevin (France) and Peter Pusey (UK)

Mon	11:00–13:00	Hall B	Lectures
Tue	09:15–09:55	Hall B	Lectures
Tue	10:40–12:40	Hall B	Lectures
Tue	15:00–15:15	Room 4	Seminars

Single particle motion in colloids: from microrheology to osmotic propulsion

12131
Mon·11:00·B

John Brady
California Institute of Technology, USA

The motion of a single individual particle in a complex material is fundamental to understanding the dynamical properties of the material. Monitoring such motion has given rise to a suite of experimental techniques collectively known as 'microrheology,' with the ability to probe the viscoelastic properties of soft heterogeneous materials (e.g. polymer solutions, colloidal dispersions, biomaterials, etc.) at the micrometer (and smaller) scale. In microrheology, elastic and viscous moduli are obtained from measurements of the fluctuating thermal motion of embedded colloidal probes. In such experiments, the probe motion is passive and reflects the near-equilibrium (linear response) properties of the surrounding medium. By actively pulling the probe through the material one can gain information about the nonlinear response, analogous to large-amplitude measurements in macrorheology. But what exactly is measured in a microrheological experiment? And how does the micro-rheological response compare with conventional macrorheology? To answer these questions, we consider a simple model—a colloidal probe pulled through a suspension of neutrally buoyant bath colloids—for which both micro- and macro-results can be obtained exactly. The moving probe distorts the dispersion's microstructure resulting in a reactive entropic or osmotic force that resists the probe's motion, which can be calculated analytically and via Brownian Dynamics simulations and used to infer the dispersion's 'effective microviscosity.' It is also shown that this out-of-equilibrium osmotic force can be generated by the probe itself to produce autonomous motion—osmotic propulsion.

Colloidal chemo-mechanics of engineering materials: clays, earth and cement

12123
Mon·11:40·B

Henri Van Damme
Ecole Supérieure Physique et de Chimi Industrielles, France

Soils and concrete are multiscale cohesive-frictional materials which owe their cohesion to the surface forces induced by their colloidal fraction: clays in earth, cement hydrates in concrete. Clay and cement hydrate (nano)particles exhibit parallel morphological (layered) and surface chemical features, with variable aspect ratio and surface electric charge. This makes them liable to a common approach. The forces between two elementary particles can be modelled either by meso-scale or by atomic-scale simulations, depending on the inter-particle distance and the dynamics of the ions and the water molecules in the inter-particle space. Properties at larger scale (cohesion, creep) are more difficult to grasp, due to the conflicting requirements for strong local inter-particle bonds on one hand and 3D long range bonding continuity on the other hand. The particle deformability appears to be a key feature in this respect.

12122
Mon·12:20·B

Colloids and microfluidics

David Weitz
Harvard University, USA

No abstract was provided.

12125
Tue·09:15·B

The hydrodynamics of self-propelled suspensions

Sriram Ramaswamy
Indian Institute of Science, India

Fish shoals, collections of swimming bacteria, and bio-filaments with motors and ATP in a living cell are all examples of ordered self-driven suspensions. My talk will survey recent progress by our group and others in extending the hydrodynamics of liquid crystals and colloids to describe the mechanics and statistics of such living matter.

11803
Tue·10:40·B

Liquid crystalline elastomers and magnetic gels: similarities and differences in their physical properties

Harald Pleiner,[†] Stefan Bohlius, Andreas Menzel, Helmut Brand and Philippe Martinoty
Max Planck Institute for Polymer Research, Germany[†]

We characterize the broken symmetries and the hydrodynamic variables for liquid crystalline elastomers and for magnetic gels. Both, static and dynamic macroscopic aspects are analyzed, in particular the elastic and rheological aspects. We discuss the width of the hydrodynamic regime as well as the cross-over to single molecule effects. Both systems share relative rotations as macroscopic variables and we investigate, in particular for liquid crystalline elastomers, their influence on the linearized as well as on the nonlinear elastic behavior. In view of the potential application as soft actuators we analyze shape changes in external mechanical and external magnetic/electric fields. We close by a critical comparison of the advantages and disadvantages of the class of materials considered here.

On the origin of the remarkable stability of aqueous foams

10513
Tue·11:00·B

Dominique Langevin,† Alfredo Martinez, Emmanuelle Rio, Giles Delon, Arnaud Jalmes and Bernard Binks
Université Paris Sud, France†

We have performed a quantitative study of the coarsening of foams stabilised solely by nanoparticles. We have used a variety of techniques: optical and electron microscopy, microfluidics, multiple light scattering. We have also performed independent studies of the particle layers at the air-water interface using other type of methods : Langmuir throughs, ellipsometry, Brewster angle microscopy. We have been able in this way to shed light on the origin of the spectacular resistance of particle-stabilised foams to coarsening. It is likely the first known foam system where coarsening is inhibited by the surface elasticity of the particle layers coating the bubble surfaces.

Self-assembly of particles for 2D lattices with adaptable spacing

10531
Tue·11:20·B

Nadine Aubry,† Sai Nudurupati, Mohammad Janjua and Pushpendra Singh
Carnegie Mellon University, USA†

While the self-assembly of particles remains challenging, it is one of the most promising approaches to nanotechnology. Among the remaining issues is the design of a technique leading to long range order and the dynamic control of the distance between the particles, while being effective on a range of particles sizes and types. We present experiments and computations showing the self-assembly of particles in 2D lattices capable of addressing these challenges. The method consists in sprinkling particles at a liquid interface and inducing an electric field normal to the interface, thus resulting in a combination of hydrodynamic (capillary) and electrostatic forces acting on the particles. The particles then organize themselves into a lattice whose spacing depends on the electric field strength. The technique works for a broad range of fluids and particles, including electrically neutral (i.e., uncharged) particles and small particles (micro- and nano-sized particles).

Microfluidic colloidal island self-assembly and erasure induced by surface acoustic waves: I. experiments

10648
Tue·11:40·B

Leslie Yeo,† James Friend and Haiyan Li
Monash University, Australia†

We demonstrate rich and complex pattern formation arising from the nonlinear dynamics associated with nanometer-order amplitude standing wave vibrations along the surface of a piezoelectric substrate upon which a small liquid drop containing a colloidal suspension is placed. At low input powers, colloidal islands assemble along the drop interface due to a combination of the surface acceleration and capillary forces acting on the colloidal particles. The position and number of these islands directly correlate with the intersection between the nodal lines of the induced interfacial capillary waves. As the input power is increased to a critical value corresponding to the onset of fluid streaming, a transient metastable state is observed in which the system oscillates between colloidal island assembly in a quiescent fluid and their erasure due to the generation of local streaming vortices.

Cross-stream migration of colloidal particles in confined flows

11718
Tue·12:00·B

Peter Daivis,† Tanya Kairn and Ian Snook
RMIT University, Australia†

We have conducted detailed studies of planar Poiseuille flow of colloidal solutions in narrow channels ranging from a few solute diameters up to more than 40 solute diameters by molecular dynamics simulations. One of the most striking observations to emerge from this study is shear-driven cross-stream migration of the solute. In this colloidal system, the solute migrates towards the walls of the channel. We have also computed the linear transport coefficients such as the thermal conductivity, viscosity, diffusion coefficients and thermal diffusion coefficients for homogeneous systems at the corresponding state points. We suggest that the concentration profile can be understood by considering a combination of thermal diffusion and shear-induced diffusion.

Hydrodynamic crystals: collective dynamics of regular arrays of spherical particles in a parallel-wall channel

11418
Tue·12:20·B

Eligiusz Wajnryb† and Jerzy Blawzdziewicz
Institute of Fundamental Technological Research, PAS, Poland†

Our accelerated Stokesian-dynamics algorithm for a system of spherical particles suspended in a fluid bounded by two parallel planar walls is used to study motion of quasi-two-dimensional regular arrays of particles in the parallel-wall geometry. The simulations are performed for square arrays of about 1000 particles moving in the center-plane of a channel with wall separation comparable to the particle diameter. Particle motion is produced either by an external Poiseuille flow or by a force parallel to the walls. The particle arrays undergo significant deformations without losing the long-range order. Under some conditions arrays can also develop an instability that is similar to the dislocation in a two-dimensional crystal. We argue that the ordered array motion is associated with the dipolar form of the quasi-two-dimensional asymptotic far-field flow produced by the particles.

Memories in paste of flow and vibration: their visualizations as crack patterns

10415
Tue·15:00·4

Akio Nakahara† and Yousuke Matsuo
Nihon University, Japan†

We experimentally find that a paste, i.e., a densely packed colloidal suspension with plasticity, has memories of external mechanical fields it suffered, such as flow and vibration. These memories are sustained as microscopically anisotropic network structures of colloidal particles. By drying these pastes, we find that the memories in pastes can be visualized as macroscopically anisotropic crack patterns, such as lamellar, radial, ring, spiral, and so on. By using the memory effect of paste, we can imprint flow patterns into pastes to control crack patterns.

Microfluidic colloidal island self-assembly and erasure induced by surface acoustic waves: II. dynamic analysis

10671
Tue·15:05·4

James Friend,† Leslie Yeo and Haiyan Li
Monash University, Australia†

A method to rapidly concentrate out micro and nanoparticles from a sessile droplet using surface acoustic waves has been developed, and though the fluid mechanics which drive the particle motion in the concentration process appears to be understood, the mechanism causing rotation of the droplet when exposed to symmetrically imparted high-frequency (10 MHz) acoustic radiation remains unexplained. Here we provide a simple model of the acoustic irradiation of the fluid and particles that causes rapid and chaotic rotation of the droplet in a manner similar to what has been observed experimentally simply due to *fast harmonic* excitation from the SAW.

The effect of temperature on strain wave superstructures on two-dimensional colloidal crystals with confinement: a Monte Carlo study

10909
Tue·15:10·4

David Chui,† Surajit Sengupta and Kurt Binder
Johannes-Gutenberg University of Mainz, Germany†

In our previous study, we showed that confinement can be used to impose a controllable mesoscopic superstructure of a predominantly mechanical elastic character on a two-dimensional colloidal crystal. Here, the effect of temperature on this kind of superstructure, interacting with an inverse power law potential, was investigated using Monte Carlo simulations. We show that the strain wave superstructures are tunable, which is crucial for its future applications in material science.

MS05 :: Classical and quantum vortex rings

Chairs: Hassan Aref (Denmark) and Carlo Barenghi (UK)

Mon	11:00–13:00	Hall A	Lectures
Tue	09:15–09:55	Hall A	Lectures
Tue	10:40–12:40	Hall A	Lectures
Thu	14:55–15:00	Hall E	Seminars

Classical vortex rings, with and without swirl

10736
Mon·11:00·A

Keith Moffatt
Cambridge University, UK

The method of magnetic relaxation for the determination of solutions of the Euler equations representing steadily propagating vortical structures will be reviewed, and compared with alternative artificial relaxation procedures that conserve the topology of the vorticity field. Attention will be focussed first on axisymmetric vortex ring configurations, for which such relaxation techniques provide simple proofs of the existence of vortex rings of prescribed 'signature', the imprint of conserved topology. Relaxation of knotted and linked configurations will be briefly considered, from which the concept of an energy spectrum of knots and links emerges in a natural way. Attention will be drawn to recent work of Buniy & Kephart (2005) seeking to identify such energy spectra with the spectrum of excitations (glueballs) in the quark-gluon plasma, in a spirit reminiscent of Kelvin's 'vortex theory of atoms' but here at the elementary particle level of quantum chromodynamics.

Vortices in quantum fluids

10149
Mon·11:40·A

Natalia Berloff
University of Cambridge, UK

Quantum fluids have been studied experimentally for many years in superfluid helium, atomic ultra-cold gases and solid-state Bose-Einstein condensates. Applications of the subject are wide-ranging, from engineering to astrophysics. Superfluid turbulence may also provide insights into classical fluid turbulence, especially at high Reynolds numbers, where the vorticity has an intermittent, fractal character. The vorticity is quantised in a superfluid in units of h/M, where M is the mass of the boson. Turbulence in the superfluid therefore resembles a tangle of vortex filaments, whose dynamics differs from that of the chaotic but continuous vorticity of classical turbulence. In my talk I shall discuss various aspects of superfluid vortices: their motion and formation, their interactions with normal fluid and travelling waves, and superfluid turbulence using the framework of the Gross–Pitaevskii equation and its modifications.

Quantum fluid questions suggested by phenomena in classical fluids **10139** Mon·12:20·A

Karim Shariff
NASA Ames Research Center, USA

No abstract was provided.

Vortex rings and their use **10152** Tue·09:15·A

Carlo Barenghi
University of Newcastle, UK

No abstract was provided.

Relative equilibria of point vortices **10034** Tue·10:40·A

Hassan Aref[†] and Rasmus Hansen
Danish Technical University, Denmark[†]

The problem of finding relative equilibria of interacting point vortices is both of intrinsic mathematical interest and of interest in applications to superfluids such as He II and BECs. We report on various efforts to solve this problem for identical point vortices: (i) Revisiting the "catalog" produced 30 years ago by Campbell and Ziff and noting several additions and edits to it; (ii) A new formula for computing the energy of a relative equilibrium which is particularly effective when the configuration is known analytically; (iii) New analytical solutions to the problem.

Alignment of strain and vorticity in vortex interactions **11159** Tue·11:00·A

Robert Kerr[†] and Miguel Bustamante
University of Warwick, UK[†]

To investigate the origin of strain and vorticity alignment in turbulent flows, new analysis of a new DNS calculation of anti-parallel vortices in the Euler equations is presented. This flow is chosen because it offers a high potential for being singular in the inviscid limit. The analysis shows that near the maximum of vorticity ($\sup|\omega|$) that the alignment of the strain and pressure satisfy new singular constraints. Whilst the middle eigenvalue of the strain is positive, which would be consistent with restricted Euler models, unlike in the restricted models the pressure Hessian is not isotropic and has a value of $\beta = e_2/(\sqrt{6}|e|) \gtrapprox 0$, barely greater than 0. Slightly further from $\sup|\omega|$, where helicity is high, $\beta \approx 0.5$, the value found for isotropic turbulence. Could this be the origin of $\beta \approx 0.5$ in turbulent flows? Circulation conservation is proposed to test numerical accuracy.

Motion of vortex rings with and without magnetic field **11581**

Yasuhide Fukumoto,† Keith Moffatt and Satoshi Ooshiro Tue·11:20·A
Kyushu University, Japan†

A general formula is established for translation speed of an axisymmetric vortex ring whose core is not necessarily thin. We rely on Kelvin–Benjamin's principle that a steady distribution of vorticity, relative to a moving frame, is a state of maximum energy, under the constraint of constant hydrodynamic impulse, on an iso-vortical sheet. By adapting this principle, we can skip the detailed solution for the flow field to extend Fraenkel–Saffman's velocity formula to third order in a small parameter, the ratio of the core to the ring radii. This formula admits to include viscosity, at large Reynolds numbers, and Saffman's formula is improved. As an extension, the velocity formulae are established for motion of a thin toroidal magnetic eddy in the MHD flows and for spherical magnetic eddies in the Hall-MHD flows.

Curvature instability of a vortex ring and a helical vortex tube **11696**

Yuji Hattori† and Yasuhide Fukumoto Tue·11:40·A
Kyushu Institute of Technology, Japan†

The curvature instability of a vortex ring and a helical vortex tube is studied analytically and numerically. For the vortex ring direct numerical simulations of the three-dimensional incompressible Navier-Stokes equations are performed in the toroidal coordinate system using spectral methods. The exponential growth of various modes due to curvature instability is captured in accordance with our previous analytical results. It is found that the vortex ring is unstable for all values of the parameter ϵ, the ratio of core to ring radius, although exact parametric resonance is limited to discrete values. For the helical vortex tube of constant curvature and torsion the curvature instability is also present since the base flow obtained by perturbation expansion is same with that of the vortex ring up to $O(\epsilon)$. Short-wavelength stability analysis reveals that the curvature instability is affected by torsion of the tube.

Vortex ring chain due to the periodic motion of a sphere **11004**

Viatcheslav Meleshko,† Russell Donnelly, Diogo Bolster and Alexandre Gourjii Tue·12:00·A
Kiev National University, Ukraine†

The talk presents the results of an investigation of the formation, stability and control of localized vortex ring structures due to a periodic motion of a sphere in an ideal incompressible fluid. The low order model based upon Dyson's vortex rings is employed. The intensity of generated vortex rings is estimated by the total vorticity, which takes place in a viscous boundary layer on the sphere. Numerical results of simulations of the transport processes in the near-wall zone, the determination of regions of low and high domains of passive admixtures are discussed. Finally we compare numerical and analytical solutions with the results of analogue laboratory experiments for helium II.

The effect of a uniform cross-flow on the circulation of vortex rings

11269
Tue·12:20·A

Eyad Hassan,† Richard Kelso and Peter Lanspeary
The University of Adelaide, Australia†

This paper describes observations and measurements of the effects of a uniform cross flow on the circulation of a laminar vortex ring ejected from an elevated pipe. We observe the growth and decay of the vortex-ring and its interaction with the shear layer which is produced by the cross flow over the surface of the elevated pipe. As the vortex ring is generated it passes through and disrupts this shear layer. We calculate a positive-core circulation on the upstream side of the vortex ring and a negative circulation on the other side. The growth rate of positive-core circulation is reduced by cancellation with the cross-flow shear-layer vorticity which is of opposite sign. The initial negative circulation is equal to the circulation of the cross-flow shear layer, but the cross flow and the cross-flow shear layer have no effect of the growth rate of the negative circulation.

Global time evolution of an axisymmetric vortex ring at small Reynolds numbers

10655
Thu·14:55·E

Felix Kaplanski† and Yasuhide Fukumoto
Tallinn University of Technology, Estonia†

An initial value problem of the Navier–Stokes equation at small Reynolds numbers for an axisymmetric vortex ring is solved. The analysis demonstrates that the found translational velocity and kinetic energy for a viscous vortex ring starting with infinitely thin core have asymptotes which coincide with Saffman's early-stage and Rott and Cantwell late-stage formulae. The comparison of the obtained velocity with Saffman's matured formula and available experimental data exhibits no significant effect of initial Reynolds number both for the matured and decaying stages. It is shown that the present model can be effective for describing laminar vortex ring formation including the case with time-dependent piston velocity program instead of Norbury's vortices.

MS06 :: Fluid dynamics of animal swimming and flying

Chairs: John Blake (UK) and Jane Wang (USA)

Mon	11:00–13:00	Hall E	Lectures
Tue	09:15–09:55	Hall D	Lectures
Tue	10:40–12:40	Hall E	Lectures
Thu	14:00–14:30	Hall D	Seminars

How insects fly

10516
Mon·11:00·E

Jane Wang
Cornell University, USA

"What force does an insect wing generate?" Finding answers to this enduring question is an essential step toward our understanding of interactions of moving objects with fluids that enable most living species such as insects, birds, and fish to travel efficiently and us to follow similar suit with sails, oars, and airfoils. Understanding force generation on a flapping wing, though a difficult feat, is only a beginning of our understanding of insects or flapping flight in nature as a whole. "Why do insects or birds flap their wings the way they do?" and "how does flapping flight come about in the course of evolution?" "Can flapping flight be more efficient and stable than a fixed-wing flight?" We give a brief history of research in insect flight and discuss recent findings in unsteady aerodynamics of flapping flight at intermediate range Reynolds numbers.

Fish swimming dynamics: knowns and unknowns

11744
Mon·11:40·E

Daniel Weihs
Technion, Israel

The elegant motions of fish moving in water have attracted the interest of scientists and engineers for centuries. While the kinematics has been studied for much of this time, the dynamics have proven to be a more difficult issue. Inviscid models such as wing theory for fins, and slender body theory for whole fish were a great advance, but this only served to pinpoint the main issue of this talk- the interaction of propulsive motions and drag. While most calculations and measurements indicate that the propulsive motions of fish increase the instantaneous drag, some studies claim the opposite. Recent work using PIV and CFD has helped clarify (and in some cases complicate) this issue. The progress in understanding whole fish, and fin propulsive motions, in the various swimming modes will be reviewed, highlighting recent results, and remaining controversies. Suggestions for future experimental, theoretical and numerical work will be presented.

Understanding swimming at low Reynolds numbers: successes and challenges

12106
Mon·12:20·E

Lisa Fauci
Tulane University, USA

Microorganisms such as bacteria and spermatozoa move in a world where viscous forces completely dominate inertial forces, and the time evolution of their motion may be thought of as a sequence of steady state snapshots. In this world, what motility strategies give rise to efficient locomotion? The study of the fluid dynamics of microorganism motility began with the classic work of G.I. Taylor in 1951, and has been an active area of research in the last decades. Current modelling challenges include the collective dynamics of microorganisms and their interactions with surrounding physical and chemical environments, coupling of their internal force-generating mechanisms with external fluid dynamics, as well as their motion through viscoelastic fluids. We will present recent work, both analytical and computational, that shed light on these complex systems.

The effect of body cross-sectional shape on glide force production in ‘flying’ snakes

11862
Tue·09:15·D

John Socha,[†] Michael LaBarbera and Kevin Miklasz
Virginia Tech, USA[†]

Flying snakes are perhaps the world’s most unconventional gliders. Although we are beginning to understand the complex motions they use while undulating through the air, we do not yet know how they specifically produce aerodynamic forces. One prominent feature of snake gliding flight is whole-body shape change from round to flattened. In this study we determine the aerodynamic characteristics of the aerial snake cross-section and test which features are most important to glide performance. Stall occurred at high angles of attack, and lift production continued well beyond stall, helping to explain robust performance of real snakes while gliding. Fore and aft downwardly-projecting ‘lips’ increased lift in the pre-stall regime; flow visualizations show that a bottom vortex forms at these angles of attack, which may augment lift. This is the first study of snake flight aerodynamics; we will additionally discuss continuing work related to the question of how snakes are able to glide.

Fluid-dynamic effects of both rigid and free boundaries on the swimming of singly flagellated bacteria

11370
Tue·09:35·D

Tomonobu Goto,[†] Tonau Nakai, Masayuki Kikuda and Yuichiro Kuroda
Tottori University, Japan[†]

The effects of a rigid and a free boundary on the swimming motion of singly flagellated bacteria, *V. alginolyticus*, which display asymmetry between forward and backward motions are investigated. The trajectory and the swimming speed affected by the two kinds of boundaries are obtained. Also, the accumulation to each boundary is measured by counting the number of the cells in the visual field of the microscope as time elapses. The influences of the two boundaries are almost similar nevertheless the fact that the rigid surface provides non-slip condition and the free boundary allows non-zero velocity. By the presence of either boundary, the backward motion is more affected than the forward motion; the cell swims faster, around in circles, and the cells accumulate to the boundary. Observed data under the effect of a rigid boundary support the image based on numerical results, which plausibly explains the asymmetric motion.

Instability of uniform suspensions of swimming micro-organisms

10330
Tue·10:40·E

Timothy Pedley
University of Cambridge, UK

An infinite, uniform suspension of swimming micro-organisms can become unstable in a variety of ways. If the cells are denser than water and swim upwards, there is a gyrotactic instability, leading to bioconvection plumes, as analysed by Pedley et al in 1988 and 1990. If the cells are neutrally buoyant and do not have a preferred swimming direction then the intrinsic stresslets of their swimming motions cause an instability whether they are pushers (thrust generated behind the body) or pullers (in front), as found by Simha & Ramaswamy in 2002 (SR). Here the analysis is repeated for the general case in which the cells may or may not be denser than water or subject to an orienting torque. The main findings are that a large enough orienting torque suppresses the SR instability, but a new mode of instability arises from the fact that the intrinsic stress is non-zero, though non-uniform, in the basic state. The results are applied to suspensions of algae, bacteria and spermatozoa.

Scaling of wake energy and propulsive efficiency of two representative jellyfish species: Aurelia and Mastigias

10901
Tue·11:00·E

Kakani Katija[†] and John Dabiri
California Institute of Technology, USA[†]

We compare the propulsive efficiency of two species of jellyfish: *Aurelia* and *Mastigias*. Both species undergo a long-distance vertical migration pattern, which suggests that they possess a high swimming efficiency. Swimming efficiency is the ratio between propulsive work (W_{prop}) and the sum of W_{prop} and the kinetic energy in the animal wake (E_{wake}). Analysis of the vortex structures in an animal wake allows for the non-invasive determination of W_{prop} from the vortex ring impulse. We present a scaling law that relates E_{wake} and animal size based on jellyfish bell radius R. The energy in a jellyfish wake, which is comprised of a vortex ring, scales as $E_{wake} \approx R^3$. Preliminary results from velocity field measurements of *Aurelia* indicate that E_{wake} follows this scaling. These findings provide experimental evidence to determine whether propulsive mechanisms used by animals are more efficient than mechanical systems.

Optimal flexibility of a flapping appendage at high Reynolds number

11133
Tue·11:20·E

Silas Alben
Georgia Institute of Technology, USA

When oscillated in a fluid, appendages such as insect wings and fish fins can produce large thrust forces while undergoing considerable bending. We attempt to understand the role of flexibility by formulating two optimization problems. Can we determine the flexibility which produces maximum thrust, or a given thrust at maximum efficiency? We present first a general model for how flexible surfaces produce vorticity and bend passively in a fluid. The model combines a nonlinear ODE for elastic bodies with a singular integral equation for a potential flow with velocity discontinuities. We solve the linearized model and find a series of local thrust optima with power-law dependences on rigidity and driving frequency. These optima are resonant peaks, damped by fluid inertia, and can be predicted with a scaling analysis. We discuss extensions to large-amplitude motions, and motions of actual fish fins.

Fluid dynamic simulation of human sperm accumulation near to surfaces

10517
Tue·11:40·E

John Blake,[†] Jackson Kirkman-Brown, Eamonn Gaffney and David Smith
University of Birmingham, UK[†]

We use a boundary-element algorithm of Pozrikidis (2002) to model the sperm head, and a variant of slender body theory to model the flagellum. The mechanisms for the accumulation of human spermatozoa near to surfaces are investigated. A planar beating, progressively motile cell with the physiological head size for human sperm, is attracted to a trajectory situated approximately 8–31 μm above the surface, depending on the wavenumber. Specialised non-planar beating is not necessary for accumulation 'near to' surfaces. We also investigate hydrodynamic theories for how beat plane inclination may or may not lead to accumulation. Cells performing a rolling 'helicoid' pattern are not predicted to exhibit finite distance boundary accumulation, but rather are deflected from the surface or reach the surface either head or flagellum-first depending on initial angle of attack.

Linked bodies swimming through a free surface

11092
Tue·12:00·E

Jules Kajtar[†] and Joe Monaghan
Monash University, Australia[†]

The swimming of linked bodies is fundamental to the study of fish and the motion of undersea robots. In this paper we describe simulations of three linked bodies moving near a free surface. The simulations use the particle method SPH (smoothed particle hydrodynamics) for both the fluid and the bodies. We test the method by simulating the drag on the bodies moving in channels and by simulations of the linked bodies swimming in an unbounded domain. The method enables us to compute the trajectory, the power expended, and the waves generated, when linked bodies swim through a free surface. The technique can be readily generalised to bodies of arbitrary number and arbitrary shape.

The upstream wake of swimming and flying animals and its correlation with propulsive efficiency

11675
Tue·12:20·E

Jifeng Peng[†] and John Dabiri
California Institute of Technology, USA[†]

The interaction between swimming and flying animals and their fluid environments generates downstream wake structures such as vortices. In most studies, the upstream flow in front of the animal is neglected. In this study, we demonstrate the existence of upstream wake structures even though the upstream flow is quiescent or possesses a uniform incoming velocity. Using a computational model, the flow generated by a swimmer (an oscillating flexible plate) is simulated and a new, Lagrangian fluid mechanical analysis is applied to the flow to identify the upstream wake structures. These upstream wake structures show the exact portion of fluid that interacts with the swimmer. A mass flow rate is defined based on the upstream wake and a metric for propulsive efficiency is established using this mass flow rate and body kinematics. We show that the upstream wake can be used to measure and objectively compare the efficiency of locomotion in water or air.

Analysis of ciliary gliding in freshwater planarians

10078
Thu·14:00·D

Takeshi Sugimoto
Kanagawa University, Japan

Freshwater planarians are too large to swim by beating the 10^{-6} m long cilia. They make use of ciliary gliding: they secrete mucus on a substratum, and glide upon it by beating ventral cilia in an antiplecticly metachronous manner. A mathematical model for this locomotion consists of the continuity of mass and the Brinkman's equation in the periciliary layer and the mucus layer. The basic equations are split into the time-averaged and time-dependent parts. The time-averaged part has the analytic solution set, whilst the time-dependent part is solved semi-analytically by use of the double-Fourier series. In the periciliary layer the flow almost creeps and the fast stream is confined near the mucus layer. Use of the typical values for the relevant parameters leads us to a paradox, for the cilium's tip speed is slower than the gliding speed itself. It is, however, possible to explain the cause of thrust by considering flip of the cilia tip owing to the buckling of the cilia.

Experimental comparison of a steady and unsteady self-propelled swimmer

11087
Thu·14:05·D

Lydia Trevino† and John Dabiri
California Institute of Technology, USA†

Aquatic animals differ from typical engineering systems in their use of unsteady flow for locomotion. Researchers have long showed interest in designing devices that resemble their shape and propulsive behaviour. The purpose of this study is to make a direct, empirical comparison between biological and engineering propulsion systems. For this study, we designed an underwater vehicle that has the capability to produce either a steady or an unsteady jet, akin to a squid and jellyfish, for propulsion while utilizing the same mechanical efficiency. The total efficiency is measured for both modes of propulsion. This avoids the need for direct measurement of propulsive efficiency and the associated use of quasi-steady models. Operational parameters of the vehicle such as pulse amplitude and frequency are varied in the study. Lagrangian methods are used to show a correlation between fluid entrainment, added-mass dynamics, total efficiency and the thrust of the vehicle.

A force element theory with applications to insect flight

11396
Thu·14:10·D

Chin-Chou Chu,† Chien-Cheng Chang and Cheng-Ta Hsieh
National Taiwan University, Taiwan†

The study presents a force theory with applications to flow about an insect wing in hovering motion, which enables us to examine force contributions to the wing from individual fluid elements. By employing an auxiliary potential function, we decompose the lift force in terms of wing surface motion, vorticity within the flow, and surface vorticity on the insect wing. The viewpoint presented provides precise identification of the various unsteady contributions. In particular, the relative importance of these unsteady components for fruit fly or dragonfly in a simplfied model of flight is quantified unambiguously to reveal the mechanisms that achieve the optimal lift.

A biomimetic figure-of-eight flapping induced by flexible wings

11473
Thu·14:15·D

Lung-Jieh Yang[†] and Cheng-Kuei Hsu
Tamkang University, Taiwan[†]

Relaxing from the conventional regarding of the rigid flapping mechanism, in this work the authors proposed to use flexible carbon-fibers and parylene films as the wing frames for palm-size micro aerial vehicles (MAVs). By combining the coupling coherent streamwise vibration of the wing frame and the driving flapping motion with one degree-of-freedom (DOF) only, a figure-of-eight stroke of wing tip trajectory is verified via a high speed camera with the wingbeat frequency beyond 20 Hz. The experiment results conclude that this biomimetic figure-of-eight flapping is done by the very nature of the aero-elastic interaction as well as the symmetry-breaking of the fluid-dynamic system rather than the delicate multi-DOF motion formulated purposely from the mechanism design.

Robustness of an insect's hovering: a transition of flapping free-flight

11474
Thu·14:20·D

Makoto Iima
Hokkaido University, Japan

Many insects flap their wings horizontally with changing the angle of attack when they hover ("normal hovering"), but it is unclear why they do so. To answer the question, we consider a model consisting of a flapping wing and the center-of-mass (CM) motion which is restricted to vertical direction. Numerical calculation of the flow and CM motion under the influence of the gravity revealed that the stable hovering is possible by horizontal flapping regardless of the detailed flapping motion. In particular, the change of the angle of attack during flapping is important: if it is restricted, CM motion during hovering flight becomes unstable. The difference between two types of flapping flight can be clarified by a transition of the minimum velocity of stable ascending flight.

The fluid mechanical basis of jellyfish feeding and the effects of prey size and escape forces

12129
Thu·14:25·D

Madeline Miller,[†] Jifeng Peng and John Dabiri
California Institute of Technology, USA[†]

In this study, a dynamical systems approach was used to study the fluid mechanical basis of feeding in moon jellyfish Aurelia aurita. The flow generated by a free-swimming Aurelia aurita was measured using digital particle imaging velocimetry. The dynamics of prey (e.g., brine shrimp Artemia) in the flow field was described by a modified Maxey–Riley equation which takes into consideration the inertia of prey and the escape forces, which can be generated by prey. A Lagrangian analysis was used to identify the region of the flow in which prey can be captured by the jelly. By comparing the size of capture regions, the effect of prey size was studied. The effects of escape forces were also studied in two types of forces. The prey inertia and escapes forces were found to help prey escape predation.

FM01 :: Boundary layers

Chairs: Kevin Cassel (USA) and Alfred Kluwick (Austria)

Tue	14:00–14:35	Hall A	Seminars
Tue	16:00–17:40	Room 3	Lectures
Wed	10:40–13:00	Room 3	Lectures

Characterising hairpin vortex packets in a low Reynolds number turbulent boundary layer

10072
Tue·14:00·A

Chong Wong,† Shuo Li and Julio Soria
CSIRO, Australia†

Two-point correlation studies from wide field-of-view Stereoscopic particle image velocimetry experiments conducted in a nominally zero pressure gradient water tunnel at $Re_\theta = 2200$ reveal coherent structures consistent with the hairpin vortex packets and boundary-layer scale structures reported in the recent literature.

Wind-tunnel studies on global unsteadiness of laminar separation bubbles

10746
Tue·14:05·A

Alexander Dovgal,† Alexander Sorokin and Victor Kozlov
Institute of Theoretical and Applied Mechanics SB RAS, Russia†

Flow perturbations amplifying at laminar boundary-layer separation behind 2D steps on a flat-plate surface were examined in a low-turbulent subsonic wind tunnel. Through hot-wire measurements two distinct bands of the separated flow instabilities were distinguished. These are short-wave convective disturbances of the separated shear layer and long-wave oscillations of the separation bubble, the latter matching the frequency range of coherent vortices shedding from the region of separation. As is found, the observed large-scale perturbations represent unsteadiness of the entire separated-flow region which is much different from the evolution of wavy shear-layer disturbances. Thus, the experimental data support an idea on separation bubbles combining amplification of the external perturbations and self-excitation. To control the global dynamics, active techniques were tried with beneficial effects upon the large-scale vortex motion induced by flow separation.

Experimental investigation of coherent structure dynamics in the outer layer of a turbulent boundary layer

11223
Tue·14:10·A

Gerrit Elsinga,† Fulvio Scarano, Andreas Schroeder, Reinhard Geisler, Christian Poelma and Jerry Westerweel
Delft University of Technology, Netherlands†

The evolution of the three-dimensional coherent structures inside a fully developed turbulent boundary layer is investigated experimentally by means of time-resolved tomographic PIV. The Reynolds number based on momentum thickness is 2000. From the measurements the velocity distribution and the spatial and temporal derivatives are obtained within a three-dimensional volume at a high temporal resolution. The objective of the present study is to detect topological features such as hairpin vortices and to follow their evolution in time, which allows establishing the temporal growth of the hairpin vortices in the outer layer as well as studying their dynamic interaction with the surrounding structures, such as large scale sweep events and other hairpin type vortices. Moreover, each term in the vorticity equation can be evaluated to gain further insight in these dynamic processes.

Bursting phenomena of boundary layer induced by 2D vortex patch **11232** Tue·14:15·A

Henryk Kudela† and Ziemowit Malecha
Wroclaw University of Technology, Poland†

Bursting phenomena induced by the near wall vortex patch in 2D is studied by numerical solution of the Navier–Stokes equation. The vortex particle method was used. The response of the wall-layer interaction was investigated in wide range of Reynolds number in order to identify dynamical feature of boundary layer that leads to sudden eruption. It was found that viscosity controls the whole process of sudden eruption. The large viscosity prevents the eruption of the boundary layer from the wall. Low viscosity caused that the bursting phenomena is accompanied by production of the cascade of small vortices and regeneration. Despite the simplicity of the model, it helps to build the intuition and enhances the understanding of the vortex interaction with solid boundary. It has fundamental meaning in the study of near wall turbulence and it has practical interest in many areas.

Mixed convection boundary layer flow from a vertical stretching sheet in a thermally stratified micropolar fluid **11263** Tue·14:20·A

Roslinda Nazar,† Anuar Ishak and Ioan Pop
National University of Malaysia, Malaysia†

The steady mixed convection boundary layer flow through a thermally stratified micropolar fluid by a stretching vertical sheet and buoyancy force is investigated. The velocity of the stretching sheet, the surface temperature and the ambient temperature are assumed to vary linearly with the distance from the leading edge of the sheet. The governing partial differential equations are first transformed into a system of ordinary differential equations before it is solved numerically by the Keller-box method. Both assisting and opposing flow cases are considered. Numerical results are presented for Prandtl number $Pr = 1$, material or micropolar parameter $K = 1$ and various values of the stratification parameter S. The results indicate that the thermal stratification affects the skin friction coefficient and the local Nusselt number. Moreover, solutions are found to exist for the assisting flow and for certain range of the mixed convection parameter for the opposing flow.

A comparison of internal and external turbulent boundary layers **11667** Tue·14:25·A

Nicholas Hutchins,† Ivan Marusic, Min Chong and Jason Monty
University of Melbourne, Australia†

This paper details a preliminary comparison between streamwise velocity fluctuations in turbulent channel flow and in zero-pressure-gradient flat-plate turbulent boundary layers. The unique facilities available at the University of Melbourne enable us to obtain these two flows at matched friction Reynolds numbers Re_τ and matched viscous-scaled hot-wire lengths l^+. We believe that this is the first time that such a precise and direct comparison has been made between internal and external wall-bounded turbulent flows. Detailed maps of energy spectra reveal important differences between these two flows, particularly in the very large-scale structures that exist in the log and inner wake regions. In the near future we plan to also obtain similar data for a fully turbulent pipe flow.

Series solution of non-similarity boundary-layer flows of non-Newtonian fluids

11104
Tue·14:30·A

Shijun Liao,† Xiangchen You and Hang Xu
Shanghai Jiao Tong University, China†

In this article, we use the non-similarity boundary-layer flows of non-Newtonian fluids over a stretching flat plate as an example to propose an analytic approach, which is based on a relatively new method for strongly nonlinear problems, namely the homotopy analysis method. The convergent series solutions are obtained, which are valid for all physical parameters and variables. The influence of the viscoelastic parameter of the non-Newtonian fluid to the skin friction and boundary-layer thickness is investigated. At the leading edge, the local coefficient of the skin friction decreases but the boundary-layer thickness increases, as the viscoelastic parameter increases. However, for all viscoelastic parameter, the local coefficient of the skin friction tends to the same value for very large x, and so does the boundary-layer thickness. This analytic approach is rather general and can be widely applied to other non-similarity boundary-layer flows.

Bifurcation phenomena in incompressible laminar ramp flow

10484
Tue·16:00·3

Alfred Kluwick,† Rene Szeywerth and Stefan Braun
Vienna University of Technology, Austria†

Recent developments in the construction of airfoils are characterised by an increasing interest in the application of smart structures for active flow control. The optimal use of such devices requires a detailed insight into the flow phenomena to be controlled. In this connection locally separated boundary layer flows are of special interest. Asymptotic analysis of such flows in the limit of large Reynolds number has shown that in a number of cases solutions of the resulting equations describing two-dimensional steady flows exist up to a limiting value Γ_c of the relevant controlling parameter Γ only while two branches of solutions exist in a regime $\Gamma < \Gamma_c$. The present study aims at a better understanding of near critical flows $|\Gamma - \Gamma_c| \to 0$ and in particular the changes of the flow behaviour associated with the passage of Γ through Γ_c. As a specific example incompressible flow past an expansion ramp is considered.

Boundary-layer breakdown in a rotating, fluid-filled torus

10446
Tue·16:20·3

Richard Clarke,† Richard Hewitt, Carlos del Pino, Jim Denier and Tom Mullin
University of Auckland, New Zealand†

It is known that the unsteady boundary layers which form on the interior surfaces of a curved pipe can break down after a finite time; we consider this effect for the case of a rotating fluid-filled torus. Boundary-layer theory is used to predict when this breakdown will occur, but cannot illuminate the structure of the flow beyond any such event. For this we turn to numerical computation of the full axisymmetric (about the rotational axis) flow, which confirm the boundary-layer-theory predictions and reveal the subsequent evolution of the flow. The resulting flow structures are connected with phenomena observed in experiments, and are believed to have repercussions for the instabilities which eventually break the axisymmetry of the flow and lead to turbulent behaviour.

On unsteady boundary-layer separation in supersonic flow

11822
Tue·16:40·3

Anatoly Ruban
The University of Manchester, UK

Assuming that the Reynolds number is large, and the the flow outside the boundary layer is supersonic, we use the method of matched asymptotic expansions to construct the corresponding solutions of the Navier–Stokes equations in a small vicinity of the separation point; the latter might move along the body surface either upstream or downstream. In both cases, the flow appears to be quasi-steady if considered in the coordinate frame moving along the body surface with the separation point. We show that the bulk of the boundary layer approaching the separation may be treated as inviscid. Still close to the body surface a thin viscous layer should be introduced. The separation is identified by a singularity forming at the outer edge of this layer. Two region of interaction between the boundary layer and external flow (one inside another) should be considered to describe the separation process. Interestingly enough, the solution for both regions can be written in a simple analytic form.

Transient growth induced by surface roughness in a Blasius boundary layer

12158
Tue·17:00·3

Philippe Lavoie,† Jonathan Morrison and Ahmed Naguib
University of Toronto, Canada†

The present work stems from an interest in model reduction for flow control: starting with a simple, linear physical model representative of near-wall turbulence, the motivation of this experiment is to devise a wall-based estimator. The inviscid, linear, transient growth regime has optimal form of spanwise periodic streamwise vortices and high/low-speed streaks. Slow growth/decay in x and spanwise periodicity suggest a reduced requirement for observability of modes. Present results indicate that a nonlinear shear is apparent in the u-disturbance profiles and that the W disturbance is asymmetric even though the periodicity of the streak/vortex pattern is preserved. In conformity with previous experiments, the transient growth region is shorter than theoretical predictions suggesting that the initial growth region is suboptimal. Future work will explore receptivity effects and measurements will be extended to include those of the two components of surface friction.

The turbulent shear stress in zero pressure gradient boundary layers

11041
Tue·17:20·3

Peter Monkewitz,† Kapil Chauhan and Hassan Nagib
Swiss Federal Institute of Technology, Switzerland†

The Reynolds shear stress, uv, in zero pressure gradient turbulent boundary layers (ZPG TBLs) is established using recently developed composite mean velocity profiles and compared with results from experiments and DNS. Using u_τ^2 for scaling, the computed stress agrees well with low-Re experimental results. However, when comparing with DNS and high Re experimental data, the good agreement is generally limited to the near-wall and outer regions, respectively. The lack of proper representation of the outer flow in the DNS and of high-precision instrumentation for near-wall measurements remain as the key reasons for such disagreement. Implications of these findings and their physical significance are highlighted.

Boundary-layer separation and vortex generation in a suddenly blocked pipe

10028
Wed·10:40·3

Jim Denier† and Nathaniel Jewell
The University of Adelaide, Australia†

This talk will present some new results on the problem of the decay of the flow within the suddenly blocked pipe. Previous work on this problem has focused upon the region away from the blockage where the flow can be shown to be unidirectional and governed by a simple diffusion equation. In the vicinity of the blockage the flow is non-planar. With a mix of asymptotic analysis and computation we are able to describe the flow within this region. Two important features are found. Firstly the decay of the flow is in some sense controlled by the flow behaviour in the blockage region where a series of unsteady boundary-layer separations generate toroidal vortices. These vortices dictate the decay time for the end region flow. The second feature that arises from our computations is that the flow in this end region is stable to axisymmetric disturbance for Reynolds number less than 3000 (the limit of our computations).

On the relationship between large- and small-scale motions in turbulent boundary layers

11734
Wed·11:00·3

Romain Mathis,† Nicholas Hutchins and Ivan Marusic
University of Melbourne, Australia†

The relationship between large- and small-scale motions remains a poorly understood process in wall-bounded turbulence. Investigation performed by Hutchins and Marusic (2007) in a high Reynolds number turbulent boundary layer has recently revealed a possible influence of large-scale log region motions on the small-scale near-wall cycle, akin to a pure amplitude modulation. For this study we build upon these observations, using the Hilbert transformation applied to the spectrally filtered small-scale component of fluctuating velocity signals, in order to determine the degree of amplitude modulation effect imparted by the large-scale structures onto the near-wall cycle.

A high Reynolds number turbulent boundary layer with regular roughness

11746
Wed·11:20·3

Jason Monty,† James Allen and Min Chong
The University of Melbourne, Australia†

Turbulence measurements from a high quality, very large boundary layer wind-tunnel at New Mexico State University are presented. The measurements are unique as they are, to the authors knowledge, the first in such a thick (0.16m) boundary layer with a rough wall. Due to the large size of the tunnel, a novel roughening solution was employed, whereby a braille printer was used to print out sheets of regularly spaced raised dots. The results show the expected inner-scaled mean velocity behaviour, while outer-scaled data show complete collapse, affirming Townsend's Reynolds number similarity hypothesis.

Non-universality of overlap region in turbulent pipe and channel flows **10437** Wed·11:40·3

Hassan Nagib,† Peter Monkewitz and Kapil Chauhan
Illinois Institute of Technology, USA†

The overlap parameters of the logarithmic region in turbulent pipe and channel flows are established using a composite profile approach which incorporates the influence of the outer part. The *Re*-specific von Karman coefficient for channel flows decreases with Reynolds number to a level below the well defined value of $\kappa_{BZ} = 0.384$ for ZPG TBLs. The proper limiting value of κ_C for the channel flow could not be established with a high confidence because of the limited range of available Reynolds numbers, but the best projected value is near $\kappa_C = 0.37$. For the pipe flow, reprocessing of the Superpipe data indicates that $\kappa_P = 0.41$. The collective behavior of κ in boundary layers, pipes and channels reveals that the von Karman coefficient is not universal, and exhibits dependence on not only the pressure gradient but also on the flow geometry, thereby raising fundamental questions regarding turbulence flow theory and modeling for all wall-bounded flows.

Sub-optimal control of unsteady boundary-layer separation in a channel with suction **10482** Wed·12:00·3

Kevin Cassel† and Chetan Sardesai
Illinois Institute of Technology, USA†

A two-dimensional channel with localized suction from the upper surface is considered as a framework within which to consider sub-optimal control of an unsteady separating boundary layer. A quasi-steady (sub-optimal) approach is adopted in which the control input is optimized at each time as the unsteady flow evolves. Two cost functionals are implemented and compared; they both use a boundary-based performance measure that minimizes the difference between the wall shear stress and a target distribution corresponding to the unseparated boundary layer. The two control mechanisms considered, with corresponding penalty functions in the respective cost functionals, are a domain-based control, involving a body force throughout the boundary layer, and a boundary-based control, including both tangential and normal wall velocities. Both control mechanisms are successful in eliminating unsteady separation, and the relative effectiveness of each approach is compared.

Towards simulations of high-Reynolds number turbulent boundary layers **11282** Wed·12:20·3

Philipp Schlatter,† Dan Henningson, Arne Johansson, Geert Brethouwer and Qiang Li
KTH Royal Institute of Technology, Stockholm, Sweden†

Direct and large-eddy simulations (DNS and LES) of spatially developing turbulent boundary layers under zero pressure gradient up to relatively high Reynolds numbers ($Re_\theta = 2500$ and above) are performed with an accurate and efficient spectral method. The computational quantities include the velocity plus passive scalars at Prandtl numbers between 0.2 and 2. The inflow is located upstream at a position where natural transition to turbulence can be expected to ensure a correct boundary-layer development. The goal of the present project is to provide reliable numerical data for high-Reynolds number wall-bounded turbulence, and to perform extensive comparisons to available measurements. To obtain the results, DNS shall be used as long as computationally justifiable, but for higher Reynolds numbers (i.e. $Re_\theta > 2500$) carefully validated LES will be employed instead. In particular, also the applicability of LES to high-Reynolds number flows shall be assessed.

Pipe flow turbulence in the presence of roughness

10729
Wed·12:40·3

Alexander Smits,[†] Marcus Hultmark, Sean Bailey, Michael Schultz and Richard Pepe
Princeton University, USA[†]

The streamwise turbulence component is measured in fully-developed turbulent flow in a commercial steel pipe for Reynolds numbers from 7.6×10^4 to 8.3×10^6, covering the smooth to fully rough regimes. For Reynolds numbers less than about 8×10^5 the surface was hydraulically-smooth, and the results agreed closely with the smooth-wall turbulence intensity and spectral data obtained earlier. An assessment was performed of probe resolution and results indicate that the turbulence statistics of the large-scale motions were unaffected by the sensing wire length even at high Reynolds numbers. Transitionally-rough and fully-rough data showed deviation from the smooth-wall data as roughness effects became more prominent. The two-point azimuthal correlations were found to be consistent with the presence of very large-scale coherent regions of low-wavenumber, low-momentum fluid observed in previous studies of wall-bounded flows.

FM02 :: Combustion and flames

Chairs: Sebastien Candel (France) and Ishwar Puri (USA)

Tue	14:00–14:15	Room 8	Seminars
Wed	10:40–13:00	Room 6	Lectures

A mechanistic model for the catalytic growth of carbon nanotubes and their combustion synthesis

10486
Tue·14:00·8

Ishwar Puri† and Sayangdev Naha
Virginia Tech, USA†

Despite the utility and promise of carbon nanotubes (CNT), their production is generally based on empirical principles. There are only a few CNT formation models that predict the dependence of their growth on various synthesis parameters. Typically, these do not incorporate a detailed mechanistic consideration of the various processes that are involved during CNT synthesis. We address this need and present a model for catalytic CNT growth that integrates various interdependent physical and chemical mechanisms involved in CNT production. We validate the model by comparing its predictions with one set of experimental measurements from a previous study for cobalt (Co) catalyzed growth. A brief parametric study is presented subsequently. From an application perspective, the model is able to predict the growth rate of the CNT length and its dependence on the ambient temperature and gas-phase feedstock partial pressure.

Characteristics of flow behaviors behind rifled nozzles

11740
Tue·14:05·8

Kuo-Ching San† and Hong-Jzen Hsu
Air Force Institute of Technology, Taiwan†

A novel rifled nozzle was installed at a traditional combustor outlet to promote the combustion efficiency. The rifled nozzle improves the momentum transmission and then increases the turbulent strength and mixing efficiency between the central fuel jet and the air swirling jet. The flow characteristics behind the rifled nozzle were visualized and detected using the smoke-wire flow visualization, particle image velocimetry, and hot-wire anemometer. The isothermal flow field is categorized into four patterns: jet flow, single bubble, dual bubble and turbulent flow by changing the Reynolds numbers of central fuel jet and air swirling jet. Furthermore, the topological scheme is utilized to analyze the flow patterns.

Thermal structures and combustion efficiency of non-premixed reacting rifled nozzles

11743
Tue·14:10·8

Shun-Chang Yen† and Hong-Jzen Hsu
National Taiwan Ocean University, Taiwan†

The target of this study is to promote the efficiency of traditional combustors using a novel rifled nozzles which was set at the outlet of a combustor. The rifle mechanism can enhance the turbulent strength and increase the mixing efficiency between central fuel jet and swirling jet by modulating the momentum transmission. To study the behavior of the rifled nozzle, the direct photography and thermocouple calibrator were used to observe the flame behavior, temperature distribution and heat release rate. The significant increase on the mixing efficiency improve the heat release rate approximately 90%. Furthermore, Five characteristic flame mode are defined: Jet flame, Flickering flame, Recirculated flame, Ring flame and Lifted flame.

OH-PLIF visualisation of radical farming supersonic combustion flows

12031
Wed·10:40·6

Russell Boyce
University of Queensland, Australia

Scramjets that employ fuel injection in the intake, followed by shock-induced combustion assisted by radical farming in the combustor, can potentially operate with shorter combustor lengths and more efficient intakes. Pressure measurements in shock tunnel models have led to the radical farm hypothesis—that even when mean combustor entry conditions are too mild for auto-ignition, localised hot pockets in the combustor cause combustion radicals to be generated, chemically frozen in expansion regions, and then available in subsequent hot pockets to accelerate ignition. Presented here are surface pressure measurements coupled with OH-PLIF visualisation of the distribution of the OH radical upstream of ignition in such a scramjet. They represent the first direct evidence in support of the existence of radical farming supersonic combustion. This is extremely significant, since it enables insight and understanding to begin of a potentially critical concept for practical scramjet vehicles.

The response of inverted flames to equivalence ratio modulations

10485
Wed·11:00·6

Sebastien Candel,[†] Sebastien Ducruix, Anne-Laure Birbaud and Daniel Durox
Ecole Centrale Paris, France[†]

Recent studies indicate that heat release fluctuations generated by equivalence ratio perturbations may constitute sources of instability with effects similar to those induced by acoustic perturbations. The present article addresses this issue by considering the dynamics of an inverted laminar V flame spreading in an open geometry when this flame is submitted to equivalence ratio modulations. The problem is investigated with numerical simulations. Calculations show that the flame features wrinkles of increasing amplitude locking on the convected equivalence ratio perturbations. For sufficiently large wrinkle amplitudes the flame interacts with the fresh mixture outer boundary giving rise to sudden disruptions of the flame sheet. This generates a nonlinear heat release signal with abrupt changes in the waveform. A simple model is devised on this basis to distinguish regimes corresponding to weak and strong interactions.

The effects of turbulence, hot spots, and stochasticity on the deflagration-to-detonation transition

10997
Wed·11:20·6

Elaine Oran,[†] Vadim Gamezo and Takanobu Ogawa
US Naval Research Laboratory, USA[†]

Multidimensional, unsteady, reactive numerical simulations have allowed us to determine a number of paths by which the deflagration-to-detonation transition (DDT) can occur in gas-phase combustion systems. In all of these pathways, a hot spot forms in a gradient of chemical reactivity, which then evolves in manner consistent with the Zeldovich gradient mechanism. In this presentation, we discuss recent simulations of spark-ignited flames propagating in channels containing arrays of obstacles, all embedded in a hydrogen-air mixture. Previous work showed that this type of scenario has well defined regimes of behavior with respect to flame acceleration and DDT. Here we discuss the effects of nonequilibrium, non-Kolmogorov turbulence on the reactive flow field, formation of reaction gradients and spontaneous waves that lead to DDT in this flow field, and effects of multiple interacting stochastic processes on our ability to predict the properties complex reactive systems.

Detonation structure for chain-branching kinetics: an analysis in the small initiation rate Limit

11090
Wed·11:40·6

Luc Bauwens,† Josue Meguizo-Gavilanes and Laurie Bedard-Tremblay
University of Calgary, Canada†

An analysis is presented for chemistry along Rayleigh lines, for a three-step chain-branching scheme in which both initiation and chain-branching are described by Arrhenius rates, but termination is arbitrary. Heat release is associated with termination only. The analysis assumes initiation is much slower than chain-branching, while activation energies are otherwise arbitrary. The structure differs for waves initiating within or without the chain-branching explosion, or in the proximity of the explosion limit. The theory is applied to ZND detonation waves. Results show that chain-branching is effective only up to a point, beyond which chemistry proceeds at a rate comparable with the small initiation rate. The reactant mass fraction at that point may remain sizable, but it drops as the von Neumann point moves further into the explosion region. Numerical simulation however shows that multidimensional cellular waves however allow for more complete reaction.

Temporally resolved pseudo-3D measurements of turbulent flame interactions using orthogonal-plane cinema-stereoscopic PIV

11599
Wed·12:00·6

Adam Steinberg,† James Driscoll and Steven Ceccio
University of Michigan, USA†

Measurements of three-dimensional turbulent structures as they interact with a premixed flame were made using a new diagnostic technique. This technique, Orthogonal-Plane Cinema-Stereoscopic PIV, allows detailed investigation of the phenomena responsible for turbulent flame stretch. Two cinema PIV interrogation planes were employed: one normal and one parallel to the flow direction. Stereoscopic measurements were taken in the normal plane, providing all three velocity components. The 3D structure of the turbulence was constructed as the flow passed through the normal plane using the resolved in-plane derivatives and employing Taylor's hypothesis for the out-of-plane derivatives. The trajectory and evolution of the turbulence as it interacted with the flame was then tracked using the parallel plane. This second plane also measured the flame front position using the PIV seed density. From these measurements, the stretch rate induced on the flame surface by the turbulence was determined.

Behaviour of stability limits of non-premixed jet flames in a co-flowing air stream

12121
Wed·12:20·6

Teresa Leung† and Ida Wierzba
University of Calgary, Canada†

The behaviour of stability limits of turbulent non-premixed jet flames in a co-flowing air stream was investigated experimentally. Particularly the effects of the co-flowing stream velocity and the presence of diluents in the fuel or air stream are discussed. Two different blowout mechanisms for lifted flames have been identified. A model for predicting blowout limits of lifted flames was developed. Results of the model are in good agreement with experimental data.

Numerical optimization of shock to detonation transition by using shaped tubes

10222
Wed·12:40·6

Ilya Semenov,† Vladimir Markov, Ildar Ahmedyanov and Pavel Utkin
Institute for Computer Aided Design, RAS, Russia†

Practical implementation of pulse detonation engines needs low-energy detonation initiation. Shock-to-detonation transition (SDT) has real advantages in comparison with direct initiation and classical deflagration-to-detonation transition. The objective of the numerical research is to optimize the shape of the tube to provide SDT for the lowest possible initial shock wave Mach number without additional energy sources. Two different designs are investigated: axisymmetrical tube with piecewise parabolic wall and tube with coil and elbows parts. The model is based on two- and three dimensional Euler equations for compressible gas mixtures. The stoichiometric propane-air mixture is used in framework of a single-step reaction. Numerical algorithm adapted for multiprocessor systems was based on finite volume method with Godunov's scheme approximation for fluxes. Discovered mechanism and optimization of SDT in shaped tubes are discussed.

FM03 :: Complex and smart fluids

Chairs: Alexander Yarin (USA) and Oliver Harlen (UK)

Tue	14:20–14:30	Room 8	Seminars
Thu	09:15–10:35	Room 10	Lectures

Coarse-graining hydrodynamic interactions in isolated polymer molecules in solution

10524
Tue·14:20·8

Prabhakar Ranganathan
Monash University, Australia

An accurate method for coarse-graining long-range hydrodynamic interactions (HI) is desirable for designing efficient simulations, particularly when no obvious spatial symmetries can be exploited, as in the case of isolated flexible polymer molecules in solution. I present results of Brownian Dynamics simulations for linear and nonlinear viscoelastic behaviour demonstrating the accuracy and viability of coarse-graining HI in a dilute polymer solution by representing a macromolecule as a chain of axisymmetric Gaussian density fields, whose instantaneous dimensions are derived from their end-to-end stretch and orientation by invoking the assumption of local equilibrium. All model parameters are uniquely related to the polymer contour length, the persistence length and the hydrodynamic diameter of the contour. The results are insensitive to the degree of coarse-graining, irrespective of whether chains are stretched in flow, or coiled near equilibrium.

Turbulence structures in turbulent boundary layer flows of cationic and non-ionic surfactant solutions

11752
Tue·14:25·8

Motoyuki Itoh,[†] Shinji Tamano, Katsuo Kato and Kazuhiko Yokota
Nagoya Institute of Technology, Japan[†]

Turbulence structures in a zero-pressure gradient turbulent boundary layer of drag-reducing cationic and non-ionic surfactant solutions were measured using a two-dimensional PIV system. The non-ionic surfactant solution (ODMAO) was the mixture of oleyldimethylamine oxide and tap water. The cationic surfactant solution (CTAC) was a mixture of cetyltrimethyl ammonium chloride with sodium salicylate as counterion, which was dissolved in tap water. For ODMAO 500 ppm solution, the turbulence was suppressed in the whole region of the turbulent boundary layer and the large-scale vortex was observed near the center of the turbulent boundary layer, which was similar to that of the drag-reducing polymer solution. For CTAC 100 ppm solution, the streamwise velocity component fluctuations were relatively large even near the center of the boundary layer, in addition to the near-wall region, which resulted in the additional maximum of the streamwise turbulence intensity.

Yielding behaviour without an explicit yield stress for soft materials **10230** Thu·09:15·10

Roger Tanner
University of Sydney, Australia

In many rheological models, for example Bingham bodies, a yield stress is specified in the model. In the case of soft deformable solids the rheological behaviour can be more complex, and in this paper we consider the the stretching and subsequent recoil after stress release of bread dough as an example of a soft solid showing yielding without specifying an explicit yield stress. It has been known since the work of Schofield and Scott Blair in the 1930s that after tensile stretching and release of stress there is a permanent set only for large enough strains, greater than about 30%—up to this point the response is elastic. The paper presents new recoil experiments on an Australian hard wheat dough and interprets these experiments via a rubber-like Lodge model with the addition of a damage function. There is no explicit yield stress, but a strain-rate dependent yield behaviour is shown by the model, thus mimicking the experiments.

Jet breakup of polymeric fluids **10365** Thu·09:35·10

Oliver Harlen[†] and Srinivas Yarlanki
University of Leeds, UK[†]

The effects of polymer additives on the break-up of jets in continuous mode inkjet printing are considered. Even at very low concentrations the presence of high molecular weight polymers can significantly affect how jets of these fluids break-up into drops. Using a finite element simulation with a moving grid technique that incorporates fluid inertia, surface tension and viscoelasticity we are able to simulate the break-up of a modulated jet in the parameter regime used in continuous inkjet printing. Nonlinear effects due to the finite amplitude of this disturbance lead to asymmetric break-up similar to that seen in inkjet printers. For the FENE-CR constitutive equation we show that high viscoelastic stresses are found both at the nozzle exit and in the thin filaments that form between drops prior to break-off and using these results we are to determine the criterion for viscoelasticity to delay break-up.

Drop impact of yield-stress fluids **10849** Thu·09:55·10

Li-Hua Luu[†] and Yoël Forterre
University of Provence, France[†]

We experimentally investigate the dynamics of drops of yield-stress fluids (polymer gel, clay) impacting rigid dry surfaces. Depending on the experimental conditions (nature of the material, hydrophilic or hydrophobic impacted surface, drop size, impact velocity), we found a rich variety of impact regimes from irreversible visco-plastic coating to elastic recoil to full bouncing. A simple model of inertial spreading, taking into account a recent rheology proposed for soft materials, allows capturing the phenomenology and gives a good estimate for the maximal radial spreading and impact time. Our study puts in evidence the crucial role of elasticity in predicting the short time, highly extensional hydrodynamics of soft yield-stress fluids. It could also help understanding more complex impact problems, such as large-scale impact cratering in planetary science.

The dynamics of visco-elastic bridges in drop coalescence

10955
Thu·10:15·10

Aleksey Rozhkov,[†] Theo Theofanous and Vladimir Mitkin
Institute for Problems in Mechanics, RAS, Russia[†]

The initial period of Frenkel's experiment on drop coalescence is employed to study viscoelastic behaviour of polymer-containing liquids in strong (high strain-rate), biaxial, extensional flow. We find that the process is governed by the balance between capillary forces and strain-originated elastic stresses, thereby allowing the means to deduce rheological properties of the material tested (such as elastic modulus and relaxation time) from measurements of the rate of growth of the liquid bridge that joins the two drops. The method is illustrated for aqueous polyethylene oxide solutions, with molecular masses of 1, 4 and 5 M, at concentrations of 1, 2 and 4% at strain rates of up to 10,000 1/s. The results compare favorably with recent data obtained with a much more elaborate setup involving the use of inertial stretching of pulse jets in conus-impact geometries (Mitkin et al., XVth International Congress on Rheology, Monterey, USA, 2008).

FM04 :: Compressible flow

Chairs: Piotr Doerffer (Poland) and Holger Babinsky (UK)

Tue	14:55–15:05	Room 5	Seminars
Wed	10:40–13:00	Hall B	Lectures

Schlieren visualisation of rocket nozzle exhaust flow

11354
Tue·14:55·5

Yvette McPhail,[†] Neil Mudford, Sean O'Byrne, Harald Kleine, Andrew Neely, Eddie Leonardi and Tracie Barber
University of New South Wales, Australia[†]

Experiments were conducted at the Australian Defence Force Academy, (ADFA), for an argon nozzle plume expanded in a quiescent helium atmosphere and an argon/helium gas co-flow in a low density helium environment. Schlieren images and pitot pressure data were obtained and the results employed as initial conditions for the Latvala and Anderson and the Nash, Whitaker and Freeman iterative methods to predict the location of the plume boundaries. The predicted plume results showed acceptable correlation with the Schlieren images and illustrated that approximate methods can be used to efficiently predict under-expanded plume boundary shapes and provide confirmation of experimental test conditions without the need for employing computationally intensive numerical codes. The Schlieren images demonstrated that relatively simple experimental apparatus and visualisation equipment can provide adequate information for hypersonic nozzle plume flows in both quiescent and co-flow environments.

The aerodynamics of aerofoils and wings in transonic ground effect

11529
Tue·15:00·5

Graham Doig,[†] Tracie Barber, Andrew Neely and Eddie Leonardi
University of New South Wales, Australia[†]

The aerodynamics of wings in ground effect are significantly different to those associated with unbounded flight. In the transonic regime, the presence of the ground not only alters the critical Mach number, but can result in destabilising shock-related effects which would not be encountered in free flight. Preliminary RANS CFD investigations have been conducted to highlight some of these effects with regards to the RAE2822 section and the ONERA M6 wing. The results highlighted great sensitivity to the variables examined; angle of attack, Mach number and ground clearance. This would have consequences for transonic ultra-low-level flight or wing-in-ground-effect aircraft. The work described will, in future, be accompanied by a full transonic wind tunnel test program.

The von Neumann paradox for strong shock reflection

10691
Wed·10:40·B

Susumu Kobayashi,[†] Takashi Adachi and Tateyuki Suzuki
Saitama Institute of Technology, Japan[†]

The von Neumann paradox is well-known among supersonic-flow researchers and it has been believed to be restricted only to weak shock reflection, although the reason was never given. We ascertained experimentally that the von Neumann paradox also exists for strong shock reflection and that the fundamental physical mechanism is the same irrespective of incident shock strength. That is to say, the oblique shock reflection in a shock tube is not rigorously pseudo-steady during the early part of impingement with a wedge, and so the basic assumption of pseudo-steadiness does not hold if the result is compared with experiments performed, using small (around 10cm) models. The reason for this non-pseudo-steadiness lies in the transport properties of fluid, i.e., viscosity and

thermal conductivity. Their existence introduces characteristic lengths to the flow system, and thus, the self-similarity does not hold. A revised von Neumann theory is applied to explain the actual phenomena.

Experimental investigation of tripping between regular and Mach reflection in the dual-solution domain

10855
Wed·11:00·B

Hans Hornung† and Christopher Mouton
California Institute of Technology, USA†

Experiments were conducted in the Mach 4.0 Ludwieg tube facility using an asymmetric wedge configuration for simplicity, following the previous work of others. The double wedge model was constructed with the lower wedge fixed and the upper wedge adjustable. First, the hysteresis phenomenon is explored. Second, tripping from regular reflection to Mach reflection by depositing laser energy onto one of the wedges is considered. The experimental results are compared with numerical computations and theoretical estimates.

Shock regularisation in dense gases by viscous inviscid interaction

10889
Wed·11:20·B

Georg Meyer† and Alfred Kluwick
Vienna University of Technology, Austria†

Transonic flows through channels which are so narrow that the classical boundary layer approach fails are considered. As a consequence, the properties of the inviscid core and the viscosity dominated boundary layer region can no longer be determined in subsequent steps but have to be calculated simultaneously. The resulting interaction problem for laminar flows is formulated for both perfect gases and dense gases with mixed nonlinearity (BZT fluids). The regularising properties of the mechanism of viscous inviscid interactions on the various shock solutions possible in the flow of dense gases with mixed nonlinearity will be discussed by showing the consistency of the solutions for the internal shock profiles due to the interaction process with admissibility criteria formulated in the literature for the inviscid case. Representative solutions for the internal structure of weak rarefaction, sonic, double sonic and split shocks will be presented.

Shock wave reflection from curved surfaces

11180
Wed·11:40·B

Beric Skews,† Harald Kleine, Christiaan Bode and Sebastian Gruber
University of the Witwatersrand, South Africa†

The flow patterns resulting from the reflection of a plane shock wave on curved surfaces has been examined using visualisation at frame rates up to 1Mfps. The patterns are different from those described in the literature, particularly in the transition from one type of reflection to another. The main diagnostics consisted of tracking very weak perturbations arising from steps on the wall, produced from the edges of strips of 0.047mm thick tape. The initial reflection consists of a compression wave which causes the shock wave to curve smoothly and which steepens up to cause a kink in the shock profile and which then becomes a Mach reflection. This reflection then becomes a Transitioned Regular Reflection but the transition point depends on the wall profile, and not on the corner signal arising from the entrance to the curved surface. New patterns for weak waves are established. Marked Kelvin–Helmholtz instabilities can arise on the shear layers under certain circumstances.

Low frequency unsteadiness in shock induced separated flows

11242
Wed·12:00·B

Sébastien Piponniau,† Jean-François Debiève, Jean-Paul Dussauge and Pierre Dupont
Université de Provence, France†

A model to explain the low frequency unsteadiness found in shock induced separation is proposed in the cases where the flow is reattaching downstream. It is based on the properties of fluid entrainment in the mixing layer generated from the separating line and it relates the low frequency motions of the shock created upstream of separation to the expansion of the separated bubble. Main aerodynamic parameters which can influence the process are precised. This model is found consistent with experimental observations obtained by PIV in a Mach 2.3 oblique shock wave/turbulent boundary layer interaction as well as with several different configurations reported in the literature.

Experiments on supersonic cavity flows with passive control

11792
Wed·12:20·B

Sudhir Gai,† Pierre Naviaux and Harald Kleine
University of New South Wales, Australia†

In spite of extended research for several decades, cavity flows in transonic and supersonic flows still pose a number of unsolved problems to the aerodynamicist, primarily because of their acoustic properties. An experimental study has been conducted to investigate the possibilities to modify the flow patterns and thus the acoustic properties of supersonic cavity flows by varying the shape of the leading and trailing edges. The primary goal was to mitigate the oscillations and their associated side effects of noise and vibration, which are typically observed in such flows. The effect of serrated edges was investigated by means of time-resolved pressure measurements and schlieren flow visualisation. Results obtained so far indicate that serrations can have a beneficial influence on the flow fields in open cavities, while it is still difficult to ascertain their effect on closed cavity flows.

European research on unsteady effects of shock wave induced separation: UFAST project

12120
Wed·12:40·B

Jean-Paul Dussauge
Centre National de la Recherche Scientifique, France

General aim of the UFAST project is to foster experimental and theoretical work in the highly nonlinear area of unsteady shock wave boundary layer interaction (SWBLI). Although in the past several projects were aiming at transonic/supersonic flows, the area of unsteady shock wave boundary layer interaction has not yet been treated in a systematic way. The main cases studied are shock waves on wings/profiles, nozzle flows and inlet flows as well as oblique shock reflection. In addition to basic flow configurations control methods (synthetic jets, electro-hydrodynamic actuators, stream-wise vortex generators and transpiration flow) are investigated. Emphasis is placed on closely coupled experiments and numerical investigations. Using RANS/URANS, hybrid RANS-LES methods and LES, UFAST will assess new methods for turbulence modelling in particular for unsteady, shock dominated flows. UFAST will shade light on the range of applicability between RANS/URANS and LES.

FM05 :: Computational fluid dynamics

Chairs: John Kim (USA) and Wolfgang Schröder (Germany)

Tue	14:00–14:55	Hall C	Seminars
Thu	11:00–12:40	Hall D	Lectures

ALE-multigrid fictitious boundary method for Navier–Stokes equations with free moving solid boundaries

10213
Tue·14:00·C

Decheng Wan
Shanghai Jiao Tong University, China

This paper deals with the numerical solutions of Navier–Stokes equations in a complex geometric domain with free moving solid boundaries by using arbitrary Lagrangian–Eulerian (ALE) and multigrid fictitious boundary method. The solid boundaries are allowed to move freely through the given mesh which is adaptively aligned by the r-type mesh deformation method, while the ALE formulation of Navier–Stokes equations is computed based on a special treatment of Dirichlet boundary conditions inside of a FEM approach in the context of a hierarchical multigrid scheme such that the flow can be efficiently computed on a simple regular computational mesh. Comparisons between the present and benchmark results for a circular cylinder oscillating in a channel are first presented, then numerical examples of vortex-induced rotation of a NACA002 wing and sedimentation of 60 particles in an incompressible viscous flow are provided to show the efficiency of the presented method.

Numerical simulation of ice accretion on airfoils

10411
Tue·14:05·C

Yihua Cao,† John Sheridan and Qiang Zhang
Beijing University of Aeronautics and Astronautics, China†

An approach based on the Eulerian two-phase flows theory to numerically simulate ice accretion on airfoils is developed. The air flowfield is obtained through Euler flow computation. The water droplets flowfield is solved through proposing a permeable wall to simulate the droplets impingement on airfoils. The droplets collection efficiency is calculated according to the droplets velocity and apparent density distribution. The thermodynamic model of ice accretion is based on the classical Messinger model and an integral boundary layer method is employed to account for roughness effect in calculating the convective heat transfer coefficient. The ice shape is built with the assumption that ice grows in the direction normal to airfoil surface. The ice accretions on NACA0012 airfoil under different icing conditions are evaluated and the comparison between the predicted results and experimental data indicates that the simulation approach developed in this paper is feasible and effective.

RANS prediction of free surface effects on the drag coefficient of an underwater hull form

10742
Tue·14:10·C

Jagadeesh Putta
The University of Western Australia, Australia

An underwater hull form moving beneath a free surface experiences an additional resistance emanating from formation of waves. In the present paper RANS simulations are carried out in order to study the effect of free surface on drag force of an underwater hull form (Afterbody1) using VOF method along with k-ϵ Realizable turbulence model for different depths of submergence and Froude numbers at zero angle of attack.

Operator-splitting scheme for a Bingham fluid in a cavity flow

11353
Tue·14:15·C

Zhenjiang You† and Raja Huilgol
Flinders University, Australia†

The lid-driven cavity flow of a Bingham fluid is studied by using the operator-splitting method. The original nonlinear problem is discretised into three subproblems: the transport problem, the multiplier problem and the Stokes problem. The three main difficulties for studying Bingham flows are then decoupled and solved seperately by using the finite element method. The numerical results, including the streamlines and yielded/unyielded regions, compare well with the ones reported elsewhere.

Adaptive finite element simulation of self-patterning phase decomposition

11871
Tue·14:20·C

Roy Stogner† and Graham Carey
University of Texas at Austin, USA†

A C^1 continuous finite element scheme with transient adaptive mesh refinement and coarsening is developed for simulation of phase separation processes described by the Cahn–Hilliard diffuse interface model of transport in mixtures and alloys. Self-assembly of patterns in the phase decomposition of thin films may be directed via control of other physics such as surface chemistry or imposed electric fields. Monte Carlo Finite Element Method simulations examine the reliability and stability of such patterning processes in thin film binary mixtures, exploring a parameter space including film thickness, temperature, initial concentration, and imposed patterning bias and examining their effects on pattern and defect formation.

Laminar displacement of viscoplastic fluids in eccentric annuli: numerical simulation and experimental validations

11524
Tue·14:25·C

Dzuy Nguyen,† Jeffery Liew, Thana Deawwanich, Wilson Chin, Peng Tonmukayakul and Mark Savery
The University of Adelaide, Australia†

In completion of oil and gas wells, zonal isolation requires proper cement placement with adequate bonding to the casing and formation. To achieve successful zonal isolation, the cement slurry must be properly designed to enable effective displacement of the drilling fluid from the wellbore annulus. The rheology, pump rate, and interfacial mixing of these fluids directly impact displacement efficiency. Reliable computational modeling of the displacement is critical to properly pre-job design and post-job analysis of the cementing job. However, a lack of experimental data exists to directly evaluate numerical predictions. To alleviate this, a transparent annular flow device with the capability of adjusting the inner-pipe eccentricity and rotation is used to study laminar displacement behavior of several viscoplastic fluids. In this paper, the results are outlined and comparisons are made between numerical simulation and experiments, illustrating the applicability of the algorithm.

DES simulations of the unsteady flow field around the Stratospheric Observatory for Infrared Astronomy

11088
Tue·14:30·C

Sven Schmid,† Thorsten Lutz and Ewald Krämer
University of Stuttgart, USA†

This paper describes results of DES-simulations of the unsteady flow over the SOFIA-platform, a 2.5m diameter reflecting telescope located in an open port on-board of a Boeing 747SP. Flow over open cavities like the SOFIA telescope port in general is characterized by unsteady flow phenomena that are excited and maintained by a self sustaining feedback process. Computed pressure spectra taken on the surface of the telescope compare well with measurement data, a good agreement can be observed in characteristic peak frequencies and amplitudes over a wide frequency range. Shear-layer visualization reveals two-dimensional Kelvin–Helmholtz like structures at the very beginning, that decay and form chaotic three-dimensional structures further downstream. Excited acoustic resonance modes could be identified at characteristic frequencies by comparing spectral pressure fluctuation patterns to acoustic eigenmodes that were computed by solving the homogenous Helmholtz Equations.

Consistency in symmetry for numerical schemes **11143** Tue·14:35·C

Marx Chhay,† Aziz Hamdouni and Pierre Sagaut
La Rochelle University, France†

Partial differential equations used in fluid mechanics problems, and more generally in transfer phenomenon, admit transformations conserving the whole set of solutions. It is known as the symmetry group of the equation. This group plays an important role in the physical properties describe by the equations, such as conservation laws and self-similar solutions. In order to conserve those properties, it is important for numerical schemes not to destroy the symmetries of the equations. Unfortunately it is not the case for most classical numerical methods. Our aim is to present ways for constructing numerical schemes that preserve symmetries, what are their geometrical properties and what numerical consequences are expected. We present a new property for numerical schemes emerging from this analysis, corresponding to a consistency in preserving symmetries. Examples from fluid mechanics problems are given in illustration.

Effect of inverted aerofoil geometry on aerodynamic performance in ground effect **11294** Tue·14:40·C

Jonathan Vogt,† Eddie Leonardi and Tracie Barber
The University of New South Wales, Australia†

A two-dimensional Computational Fluid Dynamics (CFD) study was undertaken to examine the effect of various inverted (downforce generating) aerofoil geometry configurations on the ground effect phenomena seen at low ground clearances. Simulations were conducted and comparisons made between a NACA4412 aerofoil, a Tyrrell aerofoil and three modified Tyrrell aerofoils, each modified in one location to reflect the corresponding geometry on the NACA 4412 aerofoil. The resulting pressure coefficient plots and flow field data indicate underwing ground effect suction is heavily influenced by the curvature on both sides of the aerofoil.

Shear viscosity along the freezing line of Weeks–Chandler–Andersen fluid **11415** Tue·14:45·C

Alauddin Ahmed† and Richard Sadus
Swinburne University of Technology, Australia†

We first report the freezing line viscosities of Weeks–Chandler–Andersen system. Freezing density is calculated applying a novel algorithm which combines the elements of both equilibrium and nonequilibrium molecular dynamics simulation methods. Shear viscosity along the Weeks–Chandler–Andersen fluid freezing line is calculated at different temperatures from nonequilibrium molecular dynamics simulation. The viscosity dependence on shear rate at freezing density and temperature is presented together with zero-shear rate estimation. The shear viscosity increases with temperature

along the freezing line. The calculated shear viscosity is successfully correlated in terms of the 12th-power scaling variables for freezing state points. It is found that the power law exponent is not a linear function of density as it approaches the freezing density. The behavior of fitting parameters is also analysed.

Inverse radiative problem with natural convection phenomenon **11298** Tue·14:50·C

Yun Hong[†] and Seung Baek
Korea Advanced Institute of Science and Technology, South Korea[†]

Inverse method was applied to solve a natural convective flow with gas radiation in a cavity domain. To take radiative heat transfer into consideration, the radiative transfer equation was solved by using discrete ordinate method. The unknown wall temperature distribution was estimated by using gas temperature measurements in the flow field. In present study, the inverse problem was solved through a minimization of an objective function by using the conjugate gradient method. The effects of the measurement errors and its positions on the accuracy of the estimation were also studied.

A material interface transition algorithm for multiphase flow simulation **10079** Thu·11:00·D

Marianne Francois,[†] Edward Dendy and Robert Lowrie
Los Alamos National Laboratory, USA[†]

Volume tracking method (also known as volume-of-fluid method) introduces numerical surface tension that breaks a filament into a series of droplets whenever the filament is under resolved. We propose a new approach that consists of transitioning to a continuous interface representation where volume tracking has become erroneous. The price of the continuous interface treatment is a small amount of numerical mass diffusion, even if the physical interface is immiscible. However, we have found that for certain measures, the overall accuracy is greatly improved by using our transitioning algorithm. The algorithm is developed in the context of the single fluid formulation of the incompressible Navier–Stokes equations. Numerical standard vortices advection test cases and Rayleigh–Taylor instability computations will be presented to illustrate the transition algorithm potential.

Molecular simulation of shearing dense hyperbranched polymer fluids **10983** Thu·11:20·D

Tu Le,[†] Alfred Uhlherr, Peter Daivis and Billy Todd
Swinburne University of Technology, Australia[†]

Hyperbranched polymers are imperfectly branched or irregular tree-like structures that can be synthesized economically by one-pot reaction. Due to their special physical and mechanical properties, hyperbranched polymers have potential applications in various areas such as thermoset resins, toughening agents and viscosity modifiers. In this research, molecular simulations of shearing dense hyperbranched polymer fluids have been performed using nonequilibrium molecular dynamics techniques. Trifunctional hyperbranched polymers are simulated using the coarse-grain uniform beads. Polymeric chains are composed of interconnected beads interacting via finitely extensible nonlinear elastic and Weeks–Chandler–Anderson potentials. Rheology properties and structural changes of different hyperbranched polymer melts at different strain rate are investigated. The relationship between our results and those for dendrimers and linear polymers of equivalent molecular mass are also considered.

Simulation of atomizing jets with OCT-tree adaptive mesh refinement

11848
Thu·11:40·D

Stephane Zaleski,[†] Anne Bagué, Daniel Fuster, Luis Lemoyne and Stéphane Popinet
Universite Pierre & Marie Curie, France[†]

The atomization of fuels is a critical step in many combustion processes. Recent improvements in multiphase flow simulation, as well as the increase in CPU power of typical computer architectures, allow ever more detailed simulations of atomizing jets. Recently, improved Volume-of-Fluid methods have been developped and adapted to efficient spatial discretisations such as oct-tree adaptative mesh refinement. These discretisations are combined with a full Direct Numerical Simulation (DNS) of the Navier–Stokes equations with embedded solid bodies in the Gerris GPL code (Popinet 2003). The result is that simulations of three dimensional jets, for instance of diesel fuels in high pressure air, become about to be feasible. We show some examples of atomising jets with our without the simulation of flow inside the injectors upstream. Probability Distribution Functions of droplets sizes and the influence of upstream conditions on the atomization are shown.

A dynamic wall model constrained by external Reynolds stress

11879
Thu·12:00·D

Krishnan Mahesh[†] and Noma Park
University of Minnesota, USA[†]

A new wall model for LES is proposed. Unlike conventional zonal approaches, given Reynolds stresses are not imposed as the solution, but used as constraints on the SGS stress so that the given Reynolds stress closely matches the computed one only in the mean sense. Also, since LES in general outperforms RANS even at coarse resolution except very near the wall, RANS constraints are limited to the points where the LES solution is expected to be erroneous. We use the Germano–identity error as an indicator of LES quality so that the RANS constraints are activated only where the Germano–identity error exceeds a certain bound. The proposed model is applied to LES of turbulent channel flow at various Reynolds numbers and grid resolutions to obtain significant improvement over the dynamic Smagorinsky model, especially at coarse resolutions.

Modelling the wall roughness for RANS and LES using the discrete element method

11484
Thu·12:20·D

Franco Magagnato,[†] Stefan Bühler and Martin Gabi
University of Karlsruhe, Germany[†]

The modelling of wall roughness is of great importance for example the accurate prediction of gas turbine blades or the resonance characteristic of combustion chambers. In this paper the Discrete Element Method has been implemented into our research code and extended for Large Eddy Simulation. The method has been validated and calibrated at the flat plate test case using the experimental findings of Aupoix and Spalart. The prediction of the roughness influence on a high pressure turbine blade has been investigated next. It was found that the method works very satisfactory when used with the Spalart *et al.* one equation turbulence model for RANS. The last test was done with the large eddy simulation in predicting the additional damping effect of the wall roughness influence on the resonance behaviour of a simple combustion chamber of the Helmholtz type. Here we got excellent agreement with the experiments of Arnold *et al.* for two different wall roughness values.

FM06 :: Convection

Chairs: John Patterson (Australia) and André Thess (Germany)

Mon	14:00–16:00	Hall C	Lectures
Tue	14:35–15:00	Room 8	Seminars
Thu	11:00–12:40	Hall B	Lectures

Boundary layer structure in highly turbulent Rayleigh–Bénard convection

10834
Mon·14:00·C

Ronald du Puits,† Christian Resagk and André Thess
Ilmenau University of Technology, Germany†

The heat transfer from a hot (cold) solid surface to a surrounding fluid is one of the crucial questions in thermal convection. However, especially in case of highly turbulent flows experimental results with high spatial resolution are still missing. We studied the convective boundary layer in a large-scale Rayleigh–Bénard experiment which is called the 'Barrel of Ilmenau' meeting both requirements, a maximum Rayleigh number of $Ra = 10^{12}$ and a large size of 7.15 m in diameter and 6.30 m in height. In a parameter range $10^9 < Ra < 10^{12}$ and for various aspect ratios $1.1 < \Gamma < 11$ we measured profiles of the mean horizontal velocity and the mean temperature near the cooling plate. In our paper we demonstrate that frequently used ideas of the universality of isothermal shear flows near a bounding wall can not be simply applied to the convective boundary layer.

Scaling of the local convective heat flux in turbulent Rayleigh–Bénard convection

10938
Mon·14:20·C

Penger Tong,† Ke-Qing Xia and Xiao-dong Shang
Hong Kong University of Science & Technology, Hong Kong†

Local convective heat flux $J(r)$ in turbulent thermal convection is obtained from simultaneous velocity and temperature measurements in a cylindrical cell filled with water. The measured $J(r)$ at different locations in the convection cell is found to scale with the Rayleigh number Ra as $J(r) \sim Ra^{\beta}$. The scaling exponent β at the cell center far away from the cell boundaries is found to be $\beta \simeq 0.5$, in agreement with the Kraichnan scaling for the ultimate state of thermal convection. Near the sidewall and lower conducting plate, we find $\beta \simeq 0.24$. The experiment thus provides new insight into the mechanism of heat transport in turbulent convection. Work supported by the Research Grants Council of Hong Kong SAR.

Stability of buoyancy and surface-tension driven convection in a horizontal double-diffusive layer

10418
Mon·14:40·C

Chuan Chen† and Cho Chan
University of Arizona, USA†

Experiments were conducted in a horizontal layer of stably stratified fluid with a free upper surface in a 1cm deep × 10cm long × 5cm wide tank. The density stratification was from 96 wt% ethanol-water solution at the bottom to 100 wt% ethanol at the top. Convective motion in the fluid was generated by a horizontal temperature gradient. By flow visualization we observed cellular flow patterns in planes parallel and perpendicular to the imposed temperature gradient, referred to as the transverse and longitudinal modes. Linear stability analysis was applied to an idealized parallel flow model of the fluid motion in the transverse and longitudinal modes separately. Results show that at extremely low solute gradients, the critical instability is a traveling wave in the transverse mode. At higher solute gradients, including those comparable to the observed experimental state, salt-finger instability is the most critical.

On thermal plumes in convective turbulence

10007
Mon·15:00·C

Ke-Qing Xia,† Chao Sun and Quan Zhou
The Chinese University of Hong Kong, Hong Kong†

The morphological evolution from sheetlike to mushroomlike plumes in turbulent Rayleigh-Bénard convection is investigated by simultaneous visualization of the temperature and velocity fields. The study covered a wide range of the Rayleigh number Ra and in several convection cells of different aspect ratios. The present study confirms previous findings made at a single value of Ra and also reveals new statistical and scaling properties of the thermal plumes. Moreover, individual sheetlike plumes are extracted as 2D geometrical objects and the Ra-dependence of their number statistics and geometric features are studied.

Heat and mass transfer features in magneto-polarized colloids

11362
Mon·15:20·C

Alexandra Bozhko,† Gennady Putin and Yury Bratukhin
Perm State University, Russia†

A magnetothermal convection mechanism enables the creation of a virtually arbitrary controllable body force distribution in non-conducting diamagnetic and paramagnetic materials. This mechanism is studied experimentally and analytically in an artificial magneto-polarized colloid contained in a non-isothermal spherical cavity which is placed into a uniform magnetic field. It is shown that the disturbances of magnetic field induced by the thermal variations of fluid magnetization lead to a non-threshold toroidal magneto-convective motion. When the sphere is heated from below the magnetic colloid behavior is complicated by a gravitational sedimentation of magnetic particles and their aggregates. The competition of the thermal and concentration density gradients in this case results in auto-oscillations. The current study provides insight into the nature of interaction of a magnetic field and a non-conducting fluid as well as the cause auto-oscillations in colloid systems.

Effect of the magnetic field on the flow inside droplet on a substrate

10764
Mon·15:40·C

Masayuki Kaneda,† Toshio Tagawa and Jun Fukai
Kyushu University, Japan†

The flow inside a minute droplet of paramagnetism evaporating on a lyophobic surface is numerically studied. The fluid flow is normally governed by the thermal Marangoni convection (upward along the surface) due to the small size of the droplet. Under the presence of a magnetic field, the flow pattern is affected as the elevation of a magnet. When the magnet is below the droplet, thermal Marangoni flow is suppressed and a downward flow along the surface is induced. On the contrary, when the magnet is above the droplet, the flow varies with time: initially upward flow and then the downward flow are induced. These phenomena are due to the temperature dependence of the magnetic susceptibility and the distance between the magnet and the droplet.

Direct numerical simulation of forced convection heat transfer from two staggered circular cylinders

10462
Tue·14:35·8

Sirod Sirisup† and Saifhon Tomkratoke
National Electronics and Computer Technology Center, Thailand†

Incompressible flow around a pair of circular cylinders in staggered arrangements with heated upstream cylinder is investigated in this paper. Three-dimensional direct numerical simulation (DNS) is performed using the spectral/hp element method with Reynolds numbers, Re, of 500 and 1000 and Prandtl number, Pr, of 0.71. The longitudinal separation (L) to diameter (D) ratio (L/D) and the transverse separation (T) to diameter (D) ratio (T/D) are varied from 2.5 to 5 and from 0.5 to 1, respectively. The investigation primarily focuses on local heat transfer characteristic of both cylinders. The main result in this study is that the flow configuration being $L/D = 5.0$ with both $T/D = 0.5$ and $T/D = 1.0$ leads to large interference effects on local heat transfer characteristic of the front surface of the downstream cylinder compared to the other flow configurations. The effects intensify for higher Reynolds numbers.

Two-dimensional thermal convection in a parallelogram-shaped cavity with tilted sidewalls

10819
Tue·14:40·8

Yoshinari Fukazawa† and Mitsuaki Funakoshi
Kyoto University, Japan†

The effect of inclination of sidewalls in two-dimensional thermal convection in a parallelogram-shaped cavity heated from below is investigated. The dependences of linear stability of a motionless state and the bifurcation of steady convection states associated with the increase in the Rayleigh number on inclination angle and aspect ratio are investigated numerically by the collocation method with the use of Chebyshev polynomials. It is found that the critical Rayleigh number at which the motionless state becomes unstable increases with the inclination angle of sidewalls. We also find that the Rayleigh numbers at which two steady convection states that bifurcate from the motionless state and correspond to clockwise and anticlockwise motions become unstable through subcritical pitchfork bifurcations are much different even for 10 degrees of the inclination angle.

Temperature derivatives and thermal dissipation in turbulent Rayleigh–Bénard convection

11072
Tue·14:45·8

Joerg Schumacher† and Mohammad Emran
Technische Universität Ilmenau, Germany†

We study the fine-scale statistics of the temperature and its spatial derivatives in turbulent Rayleigh–Bénard convection. Direct numerical simulations are performed in a cylindrical cell with aspect ratios larger or equal unity. Convection is in air for moderate Rayleigh numbers between 10^7 and 10^9. The differences of the active temperature field in comparison to passively advected scalar fields are discussed. Statistics of the temperature fluctuations, their spatial derivatives and the thermal dissipation rate are investigated therefore as a function of height from the bottom plate. Furthermore, the dependence of the temperature statistics on the cell aspect ratio is analysed. While the temperature statistics deviates significantly from the passive scalar turbulence case, the statistics of spatial derivatives and dissipation field behave qualitatively similarly, but is found to be more intermittent in convection.

Unsteady natural convection in a differentially heated partitioned cavity

11694
Tue·14:50·8

Feng Xu,† John Patterson and Chengwang Lei
James Cook University, Australia†

Natural convection in a differentially heated cavity has been given considerable attention. In this paper, unsteady natural convection in a partitioned cavity is numerically investigated. Results show that the transition of the natural convection flow in the cavity from an initially motionless state to a time-dependent periodic state undergoes three main stages: an initial stage, a transitional stage and a quasi-steady periodic stage. At the initial stage, vertical boundary layers adjacent to the partition and horizontal intrusions are formed, and the leading edge effect of the vertical boundary layers is observed. After the intrusions strike the isothermal sidewalls, complex flow structures arise at the downstream sections of the vertical boundary layer flows. As the core fluid is stratified, the boundary layer flows ultimately approach a time-dependent periodic flow for the present Rayleigh number, and the dominant frequency of the oscillations is 40000.

Bifurcations in convection of incompressible fluid in a rotated square cylinder

10183
Tue·14:55·8

Sergey Suslov† and Albert Sharifulin
University of Southern Queensland, Australia†

Steady two-dimensional convection is considered in a long horizontal square cylinder with two differentially heated and the two thermally insulated side walls. A cylinder is slowly rotated around its axis so that the direction of heating changes with respect to the gravity vector. A bifurcation curve in the inclination angle/Rayleigh number plane is determined which defines the parametric existence region of a stable “abnormal” solution when fluid flows down a heated surface. Such a solution is found to exist for the inclination angle of a heated lower wall up to 22 degrees. The results show that abnormal vortex solution in a square cylinder exists for a significantly wider range of governing parameters than in a circular cylinder investigated previously. This is attributed to the presence of corners and to the increased ratio of the surface area of the walls to the volume of a square cylinder in comparison with a circular one.

Viscous boundary layer measurement in turbulent thermal convection

11401
Thu·11:00·B

Chao Sun,† Ke-Qing Xia and Yin-Har Cheung
University of Twente, Netherlands†

Here we report high-resolution measurements of the properties of the velocity boundary layer in turbulent thermal convection using particle image velocimetry (PIV) technique. The measurements were made near the lower conducting plate using water as the convecting fluid, with the Rayleigh number Ra varying from 10^9 to 10^{10} with fixed Prandtl number 4.3. From the measured profiles of the horizontal velocity we obtain the viscous boundary layer thickness δ_v. It is found that δ_v follows the classical Blasius-like laminar boundary layer in the present range of Ra, and it scales with the Reynolds number Re as $\delta_v/H = 0.64Re^{-0.50\pm0.03}$ (where H is the cell height). The main conclusion of our study is that Blasius-type laminar boundary condition is a good approximation for velocity boundary layer in turbulent thermal convection for the present range of Rayleigh number and Prandtl number.

Unsteady natural convection in a reservoir model subject to periodic heating and cooling at the water surface

10773
Thu·11:20·B

Tomasz Bednarz,† Chengwang Lei and John Patterson
James Cook University, Australia†

The present experimental investigation is concerned with the transient flow response in a reservoir model subject to periodic heating and cooling at the water surface. The experimental results show stable stratification during the heating phase and unsteady mixing in the reservoir during the cooling phase. It is demonstrated that the convective flows in reservoirs subject to transient temperature changes can play an important role in the transport of nutrients and pollutants between the shallow region and the bulk deep water.

An experimental study of transient natural convection in a side-cooled cavity

11730
Thu·11:40·B

Obai Younis,† Feng Xu, John Patterson, Chengwang Lei, Jordi Pallares and Francesc Grau
Universidad Rovira i Virgili, Spain†

Natural convection has attracted numerous researchers due to a great number of applications in industry. In particular, transient natural convection in cavities is a topic of primary interest, because cavities of different geometries filled with fluid are a central component of many engineering systems. In the present study, transient natural convection in a side-cooled cavity is experimentally investigated. The shadowgraph technique is used to visualize the development of the boundary layers adjacent to sidewalls and horizontal intrusions at different stages. The results indicate that the flow development is characterized by the following distinct processes: (a) the initial growth of the vertical thermal boundary layers and horizontal intrusions; (b) the interaction of the intrusions and filling up of the cavity; and (c) the stratification and formation of double layer structures.

Modes of the convection in triaxial ellipsoid

10829
Thu·12:00·B

Aleksander Kozlov,† Nikolay Kolchanov and Gennady Putin
Perm State University, Russia†

Stability boundaries mechanical equilibrium and fields of driving parameters in which exist various, including vibrational and stochastic modes of currents are explored. Stationary, regular and stochastic modes of a convection in an ellipsoidal vacuity were studied at heating from below. Critical Rayleigh number for losses of stability of mechanical equilibrium and the critical Rayleigh number at which stationary convective current loses stability concerning oscillation perturbations is found. Records of oscillation and nonregular modes of a convection, Fourier spectrum, and also phase portraits of these modes are obtained and analysed.

Unsteady jet impingement: a systematic study of its heat transfer performance

11200
Thu·12:20·B

Heinz Herwig† and Georg Middelberg
Hamburg University of Technology, Germany†

The influence of unsteadiness with respect to the heat transfer performance of impinging jets is studied systematically by imposing various shapes and frequencies of unsteadiness. By means of an enhancement coefficient (Nusselt number of the unsteady flow over that for the steady flow) the heat transfer performance is characterized and most efficient types of unsteadiness are identified. From

PIV data of the flow field it can be concluded why certain types of unsteadiness perform well with respect to heat transfer enhancement. Finally it is shown that the influence of unsteadiness can be very different when small obstacles are added to the smooth heat transfer surface by which a more realistic situation emerges.

FM07 :: Drops, bubbles and multiphase flows

Chairs: Jacques Magnaudet (France) and Andrea Prosperetti (USA)

Mon	16:25–17:45	Hall C	Lectures
Tue	14:00–14:55	Hall E	Seminars
Thu	11:00–12:40	Hall C	Lectures
Thu	14:00–14:50	Hall E	Seminars
Thu	16:00–17:00	Hall C	Lectures
Fri	09:15–10:35	Hall C	Lectures
Fri	11:00–12:20	Hall C	Lectures

Turbulent sediment suspension and particle-fluid coupling in oscillating flows under ripple-bed conditions

11078
Mon·16:25·C

Ken Kiger,[†] Philip Knowles, Alberto Scotti and Bong Chung
University of Maryland, USA[†]

Detailed results of the distinct fluid and sediment dynamics that occur within oscillating mobile sediment beds will be presented. A simultaneous two-phase PIV method is used to measure the ensemble-mean and instantaneous motion of both phases, as well as the concentration of the particulates. The results show the details of the formation and ejection of a strong vortex at time of flow reversal which is responsible for the ejection of the sediment into the outer flow. The vortex is a significant source of turbulent transport to the outer flow, but is found to contribute less to the effective stress in the outer flow than the ensemble mean velocity. Conditional measurements of the local particle/fluid slip velocity show significant slip magnitudes within the turbulent cloud.

Shock fluidization of solids and liquids

12142
Mon·16:45·C

Vladimir Mitkin,[†] Theo Theofanous and Chee-Loon Ng
University of California, Santa Barbara, USA[†]

Unique experimental data are presented on the transformation of closely-packed, spherically-shaped, solid-particle assemblies and liquid drops (both Newtonian and visco-elastic), to disperse clouds under the action of strong shock waves. Deformation and early breakup/entrainment patterns are similar. Later dispersal behaviours differ, especially in regards to cloud-internal length scales, which are quantified along with overall cloud dimensions. The data offer opportunities for understanding visco-elastic break-up at extremely high strain rates and for testing DNS and effective-field (CFD) models of multiphase interactions at transonic and supersonic speeds, such as found in atmospheric dissemination and/or explosively-driven dispersal of solid and liquid agents.

Particle spin in rotating and shearing flows

11456
Mon·17:05·C

Johanna Bluemink,[†] Leen van Wijngaarden and Andrea Prosperetti
University of Twente, Netherlands[†]

It is known that, in a linear shear flow, fluid inertia causes a particle to spin more slowly than the surrounding fluid. The present experiments show that, surprisingly, the sphere can spin at a rate larger than the surrounding flow. In the experiment the sphere was fixed off-center, but free to rotate in a fluid undergoing solid body rotation around a horizontal axis. Numerical simulations at Reynolds number $5 < Re < 200$ confirm this observation. To gain a better understanding of the phenomenon, the rotating flow is decomposed into two shear flows along orthogonal directions. It is found numerically that one shear type has a much stronger effect on the particle spin rate than the other. The region of low stress at the back of the sphere is affected by the shear component of the incident flow. The contribution of streamwise and cross-stream shear to the particle spin can be linearly superposed for $Re = 20$ and 50.

Motion of bubbles in aqueous surfactant solutions

11481
Mon·17:25·C

Yoichiro Matsumoto,† Masato Fukuta and Shu Takagi
The University of Tokyo, Japan†

A single bubble motion in aqueous surfactant solutions is discussed. We investigate the dependence of the lift coefficient on the Langmuir number. The drag and lift forces acting on a bubble show the drastic change with the Langmuir number. Increase of Langmuir number causes the increase of the drag and the decrease of the lift. Although the pressure components and viscous stress components contributes to the drag in the same order of amplitude, they do not to the lift. For the lift, the pressure component is dominant except the high Langmuir number cases. In the high Langmuir number cases, the contribution of the pressure component disappears and the small negative lift appears by the contribution of the viscous stress component.

Bubble resonance frequencies as a function of pressure

10159
Tue·14:00·E

Richard Manasseh,† Ilija Sutalo, Andrew Ooi, Kurt Liffman, Suhith Illesinghe and Ben Aldham
CSIRO, Australia†

Experiments and theory are presented on the frequency response of gas bubbles as a function of liquid ambient pressure. An experimental system was developed to assess the accuracy of this relation. The classical volumetric resonance frequency of a bubble was modified by coupled-oscillator theory to account for the influence of a nearby surface. Experimental results showed that the surface strongly affects the resonant frequency. Theory modified for the presence of the surface was much closer to the data than the classical theory. The gradient in experimental frequency with pressure varied more than predicted. However, many factors not considered in the theory, such as the non-sphericity of the bubble, which should also vary slightly with pressure, could be responsible for this discrepancy.

Rheological properties of suspensions of noncolloidal particles in yield stress fluids

10166
Tue·14:05·E

Xavier Chateau,† Guillaume Ovarlez and Fabien Mahaut
Navier Institut, France†

We study both experimentally and theoretically the rheological properties of a suspension of non-colloidal particles dispersed in a yield stress fluid. We focus on the purely mechanical contribution of the particles to the overall suspension behavior independently of the physicochemical properties of the material. When the particles are isotropically distributed within a fluid whose behavior can be described by a Herschel–Bulkley law, closed-form estimates for the suspension overall properties as function of the solid concentration have been obtained from a nonlinear homogenization approach. Experiments with various yield stress fluids and with various particles of various sizes have been performed in order to check the validity of the theoretical results. We find that the elastic modulus-concentration relationship follows a Krieger–Dougherty law and both the yield stress and the consistency are related to the solid concentration through very simple laws.

Air cushioning and bubble entrapment in three dimensional droplet impact

11596
Tue·14:10·E

Peter Hicks† and Richard Purvis
University of East Anglia, UK†

Droplet deformation by air cushioning prior to impact is motivated by problems in aircraft icing and printing. A model will be presented coupling the free-surface deformation of a droplet to the pressure field in the narrow air layer generated as a droplet approaches an impact. In normal impacts air cushioning will be shown to deflect the free-surface upwards, delaying the moment of touchdown and trapping a bubble. In oblique impact or impact with a moving surface the region of touchdown is initially crescent shaped with air effects accelerating the moment of touchdown. The problem is studied numerically with a boundary element method modelling the evolution of the free-surface coupled to a lubrication theory in the narrow air gap between a droplet and a solid wall. Impacts between a droplet and a fluid layer will also be considered and extensions to illustrate the effect of air cushioning between general fluid shapes and solid objects will be shown.

Interaction of gaseous bubbles under the action of radiation modified Bjerknes force

11140
Tue·14:15·E

Yury Stepanyants† and Guan Yeoh
Australia Nuclear Science and Technology Organisation, Australia†

The interaction of two bubbles is studied under the action of buoyancy and radiation modified Bjerknes forces in viscous compressible fluid. Viscous drag force for an unsteady creeping flow is also accounted; it includes both the quasi-stationary Stokes and history drag forces. The bubbles are assumed having equal radii, which oscillate harmonically in time, and they are considered to be floating side-by-side during the course of motion. Such oscillation of bubble radii results, in general, in the modified Bjerknes force exerting on the bubbles. In the limit of infinite wavelength of sound waves generated by oscillating bubbles, the Bjerknes force reduces to its traditional quasi-static form. Governing equations for the interaction of two bubbles are studied analytically and numerically. Results obtained have revealed complex behaviour of two bubbles which in almost equal initial conditions, either can coalesce or draw together up to some distances but then, move away from each other.

Towards efficient modeling of cavitation erosion potential in pumps

11144
Tue·14:20·E

Patrik Zima,† Milan Sedlar and Frantisek Marsik
Academy of Sciences, Czech Republic†

The model for efficient assessment of collapse aggressiveness of cavitation bubbles in water pumps is presented. Two models are examined, one based on forces exerted by the bubble on its surroundings and the other based on energies dissipated between two successive bubble rebounds. The model is applied in the 3D Reynolds-averaged Navier–Stokes solver for the pump flow and adjusted according to pitting tests on 2D profiles in the cavitation tunnel at SIGMA RDI. The results are illustrated on the example of a mixed-flow pump impeller by comparison with the picture of the real erosion pattern and show encouraging agreement even for empirical assumptions for nuclei content in the inlet flow.

Surface profiles of collapsing cavities of splash drops

11521
Tue·14:25·E

Jong-Leng Liow† and David Cole
University of New South Wales Australian Defence Force Academy, Australia†

The axisymmetric surface profiles during the collapse of splash drops were studied for water drops impacting onto a deep pool of water. During the expansion phase, the cavity expanded in all direction, although not at equal rates. During the collapse phase, it was found that there was a quasi-stationary point of the cavity surface that existed over much of the time for collapse. This quasi-stationary point remained until the base of the cavity began to rise to form the central jet. The depth of the quasi-stationary point was found to be independent of the drop Froude number but increased with increasing impacting drop diameter. High framing rate PIV measurements at 2000 fps of the flow around the collapsing cavity suggest that the quasi-stationary point is at the node of a standing wave with the flow moving upwards above the quasi-stationary point and moving downwards below the quasi-stationary point.

Dependence of saturated vapor pressure and surface tension coefficient on radius for an argon nano-droplet

11372
Tue·14:30·E

Shigeo Fujikawa,† Hisao Yaguchi and Takeru Yano
Hokkaido University, Japan†

In a vapor-liquid equilibrium state between a droplet and its vapor, the saturated vapor pressure is usually given by Kelvin equation and the surface tension coefficient by Tolman equation, which are both derived on the basis of thermodynamics. Until now, these equations have been considered to be quantitatively invalid for a nano-droplet. Molecular dynamics (MD) simulations are performed to investigate the effect of droplet radius on the saturated vapor pressure and the surface tension coefficient for a single nano-droplet with a different radius. The simulations are executed for the equilibrium states of an argon nano-droplet of 1 to 4 nm in radius and for those of an argon planar liquid film at the temperatures of 85, 90, 95, 100 and 105 K. The surface of the planar liquid film is regarded as the surface of a droplet with infinity radius. The results certainly show that they are in rather good agreement with the thermodynamic equations.

Oscillation frequency and deformation of levitated droplets

11526
Tue·14:35·E

Tadashi Watanabe
Japan Atomic Energy Agency, Japan

The oscillations and rotations of levitated liquid droplets are simulated numerically, and the frequency shift of the shape oscillation is studied for the determination of surface tension. Three-dimensional incompressible Navier–Stokes equations are solved using the level set method. In the level set method, the level set function, which is the distance function from the droplet surface, is calculated by solving the transport equation to obtain the position of the droplet surface correctly. It is shown that the oscillation frequency decreases as the oscillation amplitude increases, while it increases as the rotation rate increases. The deformation of the droplet is found to correspond to the frequency shift of the shape oscillation. It is indicated that the measurement of the correct frequency, which is necessary for the determination of the correct surface tension, would be possible by monitoring the aspect ratio of the droplet shape and by controlling the rotation rate.

An investigation of droplets impinging on liquid film

11536
Tue·14:40·E

Jiahong Guo,† Hongxun Chen and Shiqiang Dai
Shanghai University, China†

Numerical simulation and experimental observation are performed to investigate the flow resulted from the impingement of a single droplet and the successive collision of droplets on the liquid films on the solid surface. Impingement conditions, characterized by the Reynolds and the Weber numbers, are changed by the velocity and diameter of the droplet, and by the viscosity, the surface tension and the thickness of the film. The numerical results, which agree fairly well with the experimental results, show abundant flow patterns induced by the droplets impact on the films. The mechanism for the droplets spread and crown and splash formation during the droplets impact on the films is elucidated. The roles of the velocity, diameter, viscosity and surface tension of the droplets and the thickness of the film in the impact process are discussed. It is also found that disparate flow phenomena appear when droplets impact on the film successively with different spacing between the droplets.

The zipping wetting dynamics at the breakdown of superhydrophobicity

11561
Tue·14:45·E

Peichun Tsai,† Mauro Sbragaglia, Christophe Pirat, Alisia Peters, Bram Borkent, Rob Lammertink, Matthias Wessling and Detlef Lohse
University of Twente, Netherlands†

Micro-structured hydrophobic surfaces can suspend droplets with gas pockets trapped underneath the liquid, resulting in a very low hydrodynamic resistance. This superhydrophobic state can breakdown under certain conditions, and the wetting process can reveal different dynamical aspects. The rapid dynamics at this transition is investigated experimentally, using ultra-high-speed imaging, theoretically, and numerically, using Lattice-Boltzmann simulations. Depending on the geometrical dimension of the micro-structures, the wetting fronts can propagate smoothly and circularly or—more strikingly—in a *stepwise* manner. This *square-shaped* spreading front shows multiple time scale dynamics: fluid locally pervades a new row on a slow timescale of milliseconds, whereas thereafter the row itself fills in microsecond towards the sides, i.e., perpendicular to the direction of the main front propagation ("*zipping* wetting").

Simulation of elastic objects in viscous fluid flows

11590
Tue·14:50·E

Howard Hu
University of Pennsylvania, USA

We present a numerical technique to simulate dynamics of elastic objects in viscous fluid flows. The scheme solves the deformation of incompressible elastic solids with a velocity-stress formulation, which models the solid as a "neo-Hookean" material where a partial differential equation relates the stress with the Almansi strain tensor, and the displacement field is eliminated. The coupling between the solid and fluid is enforced by assuming that the velocity and the traction force are continuous across the interface, however, the pressure and stress components are allowed to have jumps across the interface. The movement and the deformation of the objects are handled with an Arbitrary Lagrangian Eulerian (ALE) scheme. This monolithic scheme is demonstrated to be stable and is capable to resolve large deformation of the elastic objects. Results for the deformation and interaction of the elastic objects in sedimentation, simple shear flow and Poiseuille flows will be presented.

A theoretical growth model for dynamic slugs in gas/liquid horizontal pipes

10385
Thu·11:00·C

Usama Kadri,† Rene Oliemans and Robert Mudde
Delft University of Technology, Netherlands†

A new theoretical model for the growth of slugs in gas/liquid horizontal pipes has been developed. Given the flow conditions and pipe geometry, the model predicts the length and frequency of slugs. The model considers the flow rates adjoining at the front and detaching at the back of the slug. Viscous long wave length theory and slug stability model were used to calculate the liquid level in both stratified and fully developed slug flow. The change in the liquid area at the back of the slug and downstream were both considered. Special attention was given to the prediction of the transition from long to hydrodynamic slugs. The model enables us to plot lines with different final slug lengths as a function of the flow conditions. Of these lines, the 40 pipe diameter curve can be used to define the transition between long and hydrodynamic slugs. Comparisons between predictions and measurements are satisfactory.

The effect of shear on the size distribution in concentrated vesicle suspensions

10882
Thu·11:20·C

Gary Leal† and Arun Ramachandran
University of California, Santa Barbara, USA†

In this study, we explore whether shear induced collisions play a significant role in the evolution of the size distribution in concentrated vesicle suspensions. One proposed mechanism for the observed changes as vesicle suspensions age is that collisions resulting from Brownian motion, relative gravitational motion or imposed shear lead to larger structures via vesicle fusion or cluster formation, but surprisingly little is known about these processes, or how they depend on the mechanical properties of the bilayer membrane. This study consists of two parts: one is a simple study of the effect of shear rate in a Couette cell on the spatial and temporal evolution of the vesicle size distribution for systems with varied membrane compositions using differential interference contrast microscopy and light scattering; the second is an attempt to quantify the interpretation of mechanical membrane properties using the technique of micropipette aspiration.

The impulsive generation of drops at a fluid-fluid interface

11168
Thu·11:40·C

William Phillips† and Kuan-Khoon Tjan
Swinburne University of Technology, Australia†

We consider theoretically the evolution of a fluid-fluid interface set into motion by intense localized pressures caused by focused ultrasound. Depending upon the levels of gravity and surface tension, the interface is found to form either axisymmetric waves or to expel droplets which may be spherical, tear shaped or pancake like. Phase diagrams of Weber number versus Froude number and Atwood number are presented. The pinch off process which effect drops is in all cases of the power law type with exponent 2/3 and is realized as a singularity in finite time. The study was motivated by the occurrence of lung hemorrhage during ultrasonic imaging and seeks a non-thermal, non-cavitational explanation for it. Specifically, it pursues the notion that bursts of ultrasound act to expel droplets that puncture the soft air-filled sacs in the lung plural surface allowing them to fill with blood.

Microbubble pinch-off in flow-focusing devices

11548
Thu·12:00·C

Wim van Hoeve,† Benjamin Dollet, Chao Sun, Detlef Lohse and Michel Versluis
University of Twente, Netherlands†

We investigate the role of the channel geometry in the production of microbubbles by flow focusing of a gas and a liquid in a channel of rectangular cross-section. Bubble breakup occurs in two steps: a slow linear 2D collapse, followed by a final fast 3D pinch-off. We show experimentally that the aspect ratio of the channel dramatically influences the timescales of these two processes. The ultimate stage of the pinch-off yields a scaling $w_m \sim \tau^{1/3}$ between the neck width w_m and the time τ before breakup, indicating that breakup is driven solely by gas and liquid inertias and not by surface tension. In this study the gas and liquid flows are quantified using tracer particles and high-speed imaging techniques. The overall bubble breakup shows that elongated rectangular channels favors high monodispersity, whereas the highest frequency of bubble production is achieved in square geometries.

Direct numerical simulation of interface turbulence interaction

10630
Thu·12:20·C

Jean-Luc Estivalezes,† Pierre Trontin, Stephane Vincent and Jean-Paul Caltagirone
ONERA, France†

Although Large Eddy simulation of single phase flow is already widely used, Large Eddy Simulation of two-phase interfacial flow, i.e. two-phase flow where an interface separates non miscible phases, still remains a challenging task. The main issue is the development of subgrid scale models well suited for two-phase interfacial flow. In this work, we follow the same approach that was already used for single phase flow subgrid scale model development. The aim is first to generate a detailed data base from direct numerical simulation of two-phase interfacial flows and deeply analyse it. Freely decaying homogeneous isotropic (HIT) turbulence interacting with a thin planar liquid sheet has been studied by direct numerical simulation with sharp interface capturing two-phase flow solver and a detailed parametric study has been conducted based on turbulent Weber number which seems to be the relevant nondimensional parameter.

Study on the occurrence of the liquid jet and the bubble breakup in a convergent divergent channel flow

11797
Thu·14:00·E

Kazuya Shimizu,† Kazuhiro Hashiguchi, Rie Tachibana, Shintaro Takeuchi, Shu Takagi and Yoichiro Matsumoto
The Univeristy of Tokyo, Japan†

Bubble breakup can be observed in the experiment when a single bubble goes through the throat of a venturi tube. The detailed mechanism how the liquid jet is generated at the throat, however, has not been clarified by experimental observations. In this paper, therefore, numerical analysis for two-phase flow has been conducted in the axisymmetrical two-dimensional coordinate system in order to explain the bubble breakup phenomena in a venture tube flow. Numerical results successfully show the bubble breakup by the liquid jet with good agreement with experimental one. It is clearly explained that the liquid jet is generated from the bubble tail as the bubble shape becomes like a raindrop. This results from the concentration of the pressure difference behind the bubble and the convergence of the flow to the channel center when the bubble shape becomes stretched in the flow direction.

Binary droplet collision at high impact **11902** Thu·14:05·E

Kuo-Long Pan† and Ping-Chung Chou
National Taiwan University, Taiwan†

By means of a cutting technique developed recently, we have found new regimes of binary droplet collision at high Weber number, We, and identified the transition boundaries for various breakup mechanisms that shed light on the fundamental structure of droplet dynamics and further application to industrial purposes. Specifically, when We is increased beyond the generally tested range whereby separation with satellite droplets are observed, fingering structure is generated, which inhibits appearance of disintegration via the normal pinching mechanism for separation because of increased viscous dissipation. The latter structure will again be formed when We becomes sufficiently large. With further increase of We, the fingers are disrupted, leading to shattering of multiple droplets out of the circumference. The radius where the breaking occurs increases first with We and then decreases, leading to a critical We whence secondary droplets are emitted outward immediately after the impact.

Effects of interfacial waves on turbulent mass transfer in a open channel flow **11953** Thu·14:10·E

Yosuke Hasegawa† and Nobuhide Kasagi
The University of Tokyo, Japan†

We carry out numerical simulation of turbulent open channel flow and associated interfacial mass transfer in a flow regime where the interface is substantially disturbed, but not broken. Particular attention is paid to wave effects on the interfacial mass transfer. It is shown that the local mass transfer rates at both flat and wavy interfaces can be predicted fairly well from the surface divergence by Chan and Scriven's stagnation flow model. By decomposing the surface divergence into the contributions of turbulence and waves, the impact of waves on the mass transfer is discussed. It is found that the surface divergence is induced at the downstream of prominent wave crests, and the contribution of waves is comparable with that of turbulence. These results suggest the interfacial wave significantly influences the local mass transport phenomena.

Micromechanics of gas filled microballoons **11390** Thu·14:15·E

Paulo Fernandes,† Andreas Fery, Rainer Fink and George Tzvetkov
Bayreuth University, Germany†

Gas filled MicroBalloons (MBs) are today highly valued research subjects mainly due to their potential use in medical applications where they impose themselves as targeted drug delivery systems and contrast agents for ultrasonic imaging. Intense research has been devoted to the development of MB systems. It is extremely important to characterize the MBs mechanical and adhesion properties as these determine their behaviour in applications. The deformation behaviour of individual MBs is characterized with AFM Force Spectroscopy measurements. We analyze the dependence of the profiles with MB radius at different temperatures (room and body temperature). Scanning Transmission X-ray microscopy (STXM) experiments proved to be a very powerful technique to study the microballoons. Quantitative analysis of the resulting transmission profiles allowed us to characterize the microballoons radius, wall thickness, density and air content.

Inclined drop impact onto a curved surface

11874
Thu·14:20·E

Ilia Roisman,† Shamit Bakshi and Cameron Tropea
Technische Universität Darmstadt, Germany†

This theoretical and experimental study is devoted to the description of a drop impact onto a rigid smooth spherical target. The convex geometry of the target allows one to observe the expanding lamella formed by drop impact on the target surface and to measure the thickness evolution of the lamella. The influence of the liquid properties and the impact parameters (drop-to-target diameter ratio, impact velocity, impact factor) on the evolution of the thickness of the lamella is investigated. A theory for the inertia dominated, inviscid, thin liquid flow on a curved surface is developed and an analytical solution for the velocity field in the film and its thickness distribution is obtained. The theoretical model agrees well with the experimental data.

Foam films of pure liquids

12201
Thu·14:25·E

Satomi Onishi† and Vassili Yaminsky
University of South Australia, Australia†

We use film-balance to study static and dynamic interactions of 1–2 millimetre radius bubbles in surfactant-free liquids and solutions. Equilibrium films of distilled water are stabilised by surface charge associated with hydroxyl adsorption; van der Waals coalescence follows on reducing thickness below 50 nm. Vapor-saturated air bubbles in organic solvents coalesce on point contact at high and low collision speeds without forming film because the surfaces are inelastic, while the disjoining pressure, due to electric double layer repulsion, is lower than the Laplace pressure. However, surface tension gradients arising in adiabatic evaporation cooling of volatile liquids induce liquid circulation stabilising the film against rupture. Weaker in lower-volatility water, the laminar circulation is sped by electrolytes and becomes chaotic. Negative surface activity of ions complements the cooling effect. Surface elasticity stabilises aqueous films in viscous drainage to inertial collapse.

Capillary ratchet: hydrodynamics of surface tension feeding in shorebirds

11674
Thu·14:30·E

Manu Prakash,† John Bush and David Quéré
Massachusetts Institute of Technology, USA†

Bird beaks are highly specialized for different foraging strategies, hence the diversity of beak shapes observed in nature, from Darwin's finches, to hummingbirds, to crossbills. A number of shorebirds with needle-like beaks employ a novel feeding mechanism: where food-bearing droplets are transported mouthward by repeatedly opening and closing the beak in a tweezering motion. We here elucidate the subtle hydrodynamics and surface physics involved in capillary feeding. While contact line pinning typically acts to resist droplet motion. We demonstrate that, in capillary feeding, it couples to the time-dependent beak geometry corresponding to the mandibular spreading cycles, thereby driving drop motion via a ratcheting mechanism. Furthermore the system may be tuned by prescribing beak opening and closing angles that optimize the drop transport. Finally, the capillary ratchet may find applications in microscale fluid transport, such as valveless pumping in droplet microfluidic devices.

On the formation and cavity dynamics of big floating bubble by drop impact onto liquid pool

11818
Thu·14:35·E

Chen-Chi Kuan,† An-Bang Wang and Fei-Yau Lu
National Taiwan University, Taiwan†

In the present study, formation and cavity dynamics of big floating bubble induced by the droplet impact has been experimentally studied and analyzed. Effects of impact velocity, drop size, oscillation parameter and depth of target liquid have been investigated and discussed. The oscillation parameter, sharpness ratio e, of free-falling droplet, defined as the ratio of maximum length of droplet in the vertical to the horizontal direction before impact and Weber number have been found to be the most important controlling parameters. Furthermore, an improved quantitative tracking method has been used to analyze the cavity dynamics of the big floating bubbles generated by the drop impacting onto deep liquid pool. Similarity appears in the cavity developing process and the ratio of time scales for reaching the maximum withdrawing velocity and the maximum cavity depth has been found as an invariant for all investigated cases.

New types of a single bubble motions in dilute surfactant solution

11745
Thu·14:40·E

Yoshiyuki Tagawa,† Yoichiro Matsumoto, Ami Funakubo and Shu Takagi
University of Tokyo, Japan†

Path instability of a single bubble rising in a quiescent liquid is one of the most important topics of bubble dynamics. Similar to the previous studies, we observed typical three types of path instabilities: zigzag motion, spiral one, and transitional one from zigzag to spiral in super purified water. In this presentation, we focus on surfactant effect on path instability because surfactant has a drastic effect. We measured bubble trajectories in dilute surfactant solution. Two new types of motions are observed: transitional motion from spiral to zigzag which is an opposite transition compared to the case of super purified water, and first from zigzag to spiral, then spiral to zigzag. These path instabilities have never been observed in super purified water. We discuss these interesting results by unsteady surfactant absorption on a bubble surface. We will discuss its mechanics in detail in our presentation.

Submerged gas jet interface stability

11872
Thu·14:45·E

Chris Weiland,† Jon Yagla and Pavlos Vlachos
Virginia Tech, USA†

The stability of a gas jet submerged in water at both subsonic and supersonic speeds was studied experimentally. The experiments were conducted in a large Plexiglas tank and high speed photography of the gas-liquid interface was used to study its dynamic characteristics. The interface position was measured using a high speed digital camera ($\sim$ 3 kHz) and calculated automatically using image processing techniques. A Proper Orthogonal Decomposition (POD) analysis of the interface position in time was used to analyze the dynamics of the evolving interface. Results indicate that the interface can be reduced into a number of fundamental spatial modes that are well modelled analytically. Comparisons of the mode shapes with prior experiments show that the helical modes are suppressed for supersonic jets using the planar system, thus indicating that helical modes do exist along the interface as predicted by perturbation analysis.

Memory-encoding shape vibrations in a disconnecting air bubble **11645** Thu·16:00·C

Wendy Zhang,† Sidney Nagel, Nathan Keim and Laura Schmidt
University of Chicago, USA†

Here we show that the classic approach of modeling the disconnection of an underwater air bubble as a 2D Rayleigh–Plesset collapse provides a simple explanation for recent observations that the disconnection is exquisitely sensitive to slight asymmetries in the bubble neck shape. The cylindrically symmetric inviscid collapse is Hamiltonian, thus naturally possessing a complete memory of the energy distribution initiating the disconnection. Surprisingly, a linear stability analysis of the singularity dynamics controlling the final moments of the disconnection shows the singularity has a precise memory of the azimuthal energy distribution. This memory is encoded by constant-amplitude vibrations in the cross-section shape of the bubble neck. We excite these memory-encoding shape vibrations experimentally by causing an air bubble to detach from a slot-shaped nozzle. The measured vibration dynamics is also quantitatively consistent with the stability results.

Geometric confinement suppresses jet break-up in microfluidic channels **11445** Thu·16:20·C

Katherine Humphry,† David Weitz, Howard Stone, Alberto Fernández-Nieves and Armand Ajdari
Harvard University, USA†

We probe the stability of a flowing fluid jet surrounded by a second immiscible co-flowing fluid in microfluidic channels. We demonstrate that geometric confinement determines whether the jet breaks into drops or remains stable: When the width of the jet is comparable to or larger than the height of the channel, capillary instabilities are suppressed and the jet persists. We develop a simple theoretical model that correctly describes our experimental observations.

Discontinuous flow in the thinning process of viscoelastic filaments **11514** Thu·16:40·C

Christian Wagner,† Rainer Sattler and Jens Eggers
Universitaet des Saarlandes, Germany†

We present experimental measurements on the thinning process of a viscoelastic capillary bridge. When a tiny amount of flexible polymers is added to a Newtonian solvent the typical self similar scenario of the break up dynamic is dramatically altered and a cylindrical thread is formed instead. Whilst the polymers get more and more stretched, the filament thins exponentially in time and remains robust against distortions. Finally, when the polymers get fully stretched and the filament is only a few microns thick, a rich instability scenario takes place that ends in a blistering process and eventually in the formation of solid polymeric nano fibers. But already in the stage of exponential thinning the flow might become discontinuously and the final break up is triggered by a precursor, given by a local instability at the ends of the filament at the transition to the falling droplet or the reservoir.

Impact of drops of complex liquids on a small target **11579** Fri·09:15·C

Michele Vignes-Adler,† Bernard Prunet-Foch and Aleksey Rozhkov
Université Paris Est, France†

We are presenting an experimental and theoretical study of drops of surfactant solutions impacting a target of same diameter at high Weber and Reynolds numbers. Upon collision, the drop is transformed into a thin lamella with free surfaces bounded by a thicker toroidal rim giving rise to splashes in a way which depends on the nature of the additives and their concentration in solution.

The high and fast deformation of the drop liquid dramatically changes the physical properties in particular the surface properties. The relaxation of the drop is drastically dependent of the nature of the surfactant, more precisely of its adsorption kinetics. We have calculated the drop dynamics and analyzed the influence of the dynamic properties of the surface-active solutions on the drop transient behavior.

Translational dynamics of an acoustically coupled microbubble pair in an ultrasound field

11658
Fri·09:35·C

Michel Versluis,† Valeria Garbin, Benjamin Dollet, Leen van Wijngaarden, Nico de Jong and Detlef Lohse
University of Twente, Netherlands†

Micron-sized gas bubbles are injected in the blood flow to enhance the image quality in ultrasound medical imaging. Bubble-bubble interactions are important for the optimization of diagnostic imaging protocols. Here we study the translational dynamics of two contrast agent microbubbles in an ultrasound field, their mutual attraction being due to the secondary Bjerknes force. We isolate and position a bubble pair using optical tweezers, and optically record their dynamics using an ultra-high speed camera at 15 million frames per second. The combined setup enabled us to observe purely the effect of the acoustic coupling, and it revealed that the attracting bubbles undergo translatory oscillations around a position that is slowly drifting. To account for this effect, in our model we included the viscous drag in the form of Stokes' solution for an oscillating sphere and found excellent agreement with the experimental data.

Bubble/microcantilever interactions in a confined channel

11668
Fri·09:55·C

Ellen Longmire,† Matthew Stegmeir and Susan Mantell
University of Minnesota, USA†

The impact of bubbles of diameter 0.4–2 mm with static microcantilever obstacles aligned with the mean flow direction in vertical channels was investigated. Channel Reynolds numbers were 800-2400, and the effects of bubble Weber number and offset as well as beam offset from the channel centerline were investigated. Multiple types of interactions were observed including bouncing with little deformation, wrapping, and splitting in two. These interactions were characterized in terms of the input parameters and explained in terms of the relevant forces and moments acting on the bubbles. A minimum Weber number ~ 3 was required for splitting. For smaller bubbles compared to the channel width ($D/w < 0.6$), the minimum We increased for increasing bubble offset. For larger bubbles ($0.6 < D/w < 0.75$), splitting was more likely at lower We and higher offsets because of cross stream lifting moments that rotated the bubbles partially around the beam, increasing bubble/beam interaction times.

Direct simulation of unsteady three-dimensional core-annular flows with high viscosity ratio

11857
Fri·10:15·C

Jie Li
University of Cambridge, UK

A highly efficient numerical method was developed to calculate asymmetric three-dimensional flows of two immiscible liquids in a circular pipe. The incompressible Navier–Stokes equation was solved by a semi-implicit projection method where an Arbitrary Lagrangian–Eulerian (ALE) spatial discretization is particularly efficient for the curvilinear grid layout. A volume of fluid (VOF) method was used to explicitly track the interface between two-liquids in the curvilinear coordinate system.

The heavy oil transport in a pipeline was investigated. This is a problem of practical importance due to the significant increase in energy demand. Simulations of these flows are challenging because of the inherent three-dimensional flow characteristics and to the best of our knowledge, this is the first successful attempt.

Interaction of a shock wave with multiple gas bubbles in water

11627
Fri·11:00·C

Stephen Shaw,† Omar Matar and Peter Spelt
Imperial College London, UK†

The propagation of both strong and weak shock waves through water containing a number of compressible gas bubbles is considered numerically. Both the gas and liquid phases are modelled by the compressible Euler equations together with suitable equations of state. In each phase the pertinent equations are solved using a third order Eno-Roe scheme to evaluate spatial derivatives whilst quantities are evolved temporally using a third order TVD Runge–Kutta method. The interface between the two phases is tracked using a level set function. Ghost cells are also employed at the interface to prevent non-physical oscillations in the solution variables together with the isobaric fix technique. Our scheme is employed to consider bubble/shock interactions in 2D cartesian, axisymmetric and fully 3D cartesian coordinates. Comparisons are made with compressible Rayleigh–Plesset type equations to access for what shock strengths significant deviations occur.

Liquid effects on the unsteady motion of a collision-dominant solid-liquid flow: experimental investigations and DEM simulations using a 'wet' collision model

11441
Fri·11:20·C

Fu-Ling Yang,† Chen-Shan Chen, Shang-Hsien Hsieh and Wei-Tze Chang
National Taiwan University, Taiwan†

This work investigates how a liquid constituent modifies the bulk behaviour of a collision-dominant solid-liquid two-phase flow down a laboratory flume, with a focus on the characteristic time and velocity of the bulk motion. Dimensionless parameters that characterize the mixture dynamics at the flow and the particle level will be examined, including the Savage number, the Bagnold number, the particle Reynolds number, and the particle Stokes number. New parameters that characterize the unsteadiness and the heterogeneity will also be introduced and applied to correlate the microscopic and macroscopic flow mechanisms. A discrete-element simulation is also attempted in which the liquid effects are considered employing a semi-empirical wet collision model that predicts liquid modified DEM parameters.

Evolution of neutral and charged drops in an electric field

11636
Fri·11:40·C

Ultano Kindelan† and Marco Fontelos
Universidad Politécnica de Madrid, Spain†

We study the evolution of drops of a very viscous and conducting fluid under the influence of an external electric field. The drops may be neutral or may be charged with some amount of electric charge. If both the external electric field and total drop charge are sufficiently small, then prolate spherical shapes develop according to Taylor's observations. For sufficiently large charge and/or external field a self-similar cone-like singularity develops in a mechanism different from Taylor's prediction. The opening semiangle of the cones both for uncharged and charged drops in a constant electric field is typically around 30° with a very slight dependence on the viscosity ratio and independence from both total charge and external field. We also discuss the structure of electric and velocity fields near the tip.

Electrophoresis of gas bubbles

10954
Fri·12:00·C

John Harper
Victoria University of Wellington, New Zealand

Electrophoresis occurs when a charged particle in a liquid is set in motion by an externally imposed electric field. Oppositely charged ions are attracted to the particle, so an electrical double layer forms around it. If the particle is rigid and the double-layer thickness much smaller than the particle size the theory has been known for over a century, and it agrees well with experiments. But for non-conducting bubbles and drops various theories give various results, and all of them disagree with the experimental data. That seems surprising, as the physical chemistry is the same as in the rigid-body case, and only the fluid mechanics and the convective diffusion of ions would seem to be different. This talk will explore the difficulties.

FM08 :: Experimental methods in fluid mechanics

Chairs: Cameron Tropea (Germany) and Jerry Westerweel (Netherlands)

Mon	14:00–16:00	Hall D	Lectures
Thu	14:40–14:55	Room 6	Seminars
Fri	09:15–10:35	Hall D	Lectures
Fri	11:00–11:40	Hall D	Lectures

Delta surface hot-wires as a means of measuring wall shear stresses at arbitrary flow directions

11757
Mon·14:00·D

Christoph Dobriloff[†] and Wolfgang Nitsche
Berlin University of Technology, Germany[†]

The present paper introduces a new measuring technique based on surface hot-wires, which allows quantitative wall shear stress measurements at arbitrary flow directions. This is achieved by combining three surface hot-wire sensors with asymmetric cavities beneath the sensing element in a specific triangular (or delta-) arrangement. The calibration procedure for these triple-probes is explained and the algorithm for the wall shear stress vector extraction from the measured voltage signals is discussed. Calibration measurements have been performed for single probes as well as a linear array of 14 probes. Additionally, first measurements under subsonic 3D-flow conditions have been conducted in the vicinity of a wall mounted circular cylinder and show good results regarding the typical wall shear stress ditribution around circular cylinders.

Lorentz force velocimetry: theory and practice

10493
Mon·14:20·D

André Thess,[†] Vitaly Minchenya, Yurii Kolesnikov and Christian Karcher
Ilmenau University of Technology, Germany[†]

We describe a non-contact technique for velocity measurement in electrically conducting fluids. The technique, which is termed Lorentz force velocimetry (LFV), is based on exposing the fluid to a magnetic field and measuring the force acting upon the magnetic-field-generating system. We illustrate the physical principles of LFV, formulate the general theory and report results of comprehensive laboratory experiments which characterise the sensitivity of LFV. We further present results of industrial tests of the technique in the aluminium industry which demonstrate that LFV performs well under harsh industrial conditions. We finally outline some future developments and argue that LFV, if properly designed, has a wide range of potential applications in metallurgy, semiconductor crystal growth and possibly glassmaking.

Measurement of unsteady surface forces by means of pressure sensitive copolymer coatings

11609
Mon·14:40·D

Jan Domhardt,[†] Wolfgang Nitsche, Inken Peltzer and Janin Leuckert
Berlin University of Technology, Germany[†]

Pressure Sensitive Copolymer Coating (PSC) with piezoelectric properties is introduced as a new surface measurement technique for unsteady pressure fluctuations. PSC was developed to enable high spatial and temporal resolution and can be sprayed onto arbitrarily formed surfaces. The measuring principle of PSC is based on the direct piezoelectric effect with its linear relationship between electrical polarisation and mechanically applied force. To determine the piezoelectric voltage constant g_{33} of the coating, calibration measurements have been carried out. Furthermore, investi-

gations of the unsteady flow around a wall mounted cylinder have been executed. In this context, measurements on the lateral surface area and in the wake of the cylinder with a high temporal resolution were performed. The footprints of the characteristic alternating vortices in the wake could be identified and separation phenomena on the lateral surface were successfully detected.

Global Doppler imaging with near-resonant interferometry

10898
Mon·15:00·D

Andrin Landolt† and Thomas Roesgen
ETH Zurich, Switzerland†

The possibility of recording flow velocity distributions using the anomalous dispersion of an atomic line filter is demonstrated. With the filter placed in one leg of an imaging interferometer, any Doppler shift in the scattered light will result in a local distortion of a suitable carrier fringe pattern recorded at the image plane of the interferometer. By applying the Kramers–Kronig relations to obtain the refractive index from available absorption data, the performance of the method using an Iodine vapor cell was assessed. The model predictions were found to agree well with the experimental calibration. The method and the setup were validated and calibrated experimentally with a rotating disc. The capability of the technique to operate in a real experimental environment was demonstrated in a free subsonic jet and a tip vortex flow behind a wing section in a medium-sized wind tunnel facility. The measurements were in good agreement with the reference data.

Control of the depth of correlation in micro-PIV using a novel post-processing method

11702
Mon·15:20·D

Chuong Nguyen,† Josie Carberry and Andreas Foudras
Monash University, Australia†

In micro PIV, volume illumination affects significantly the depth of the images that contributes to the correlation. Consequently, the measurement is a weighted average of the flow within the depth of correlation. For relatively large correlation depths this may result in distortion of the correlation peak and large measurement errors. It is therefore desirable to reduce the depth of correlation. We present a novel application of image overlapping to effectively reduce the depth of correlation and improve the measurement accuracy. This technique is particularly effective in boundary flows where velocity gradients are large. This short paper will present results of image overlapping applied to synthetic data.

Pressure and temperature measurements of supersonic microjet impingement

11923
Mon·15:40·D

Chihyung Huang,† John Sullivan and James Gregory
Purdue University, USA†

In this paper, pressure and temperature profiles of supersonic microjet impingement were investigated with pressure and temperature-sensitive paint. 1 mm and 0.4 mm microjet were selected to study with different impinging angles from 10, 30, and 90 degree. The distance between impinging jet and flat surface was used as distance/jet diameter of 8.42 to 3.51. The total pressure in the chamber was varied from 24.5 to 74.5 psia. Shock wave patterns have been observed in the pressure data for both 1 mm and 0.4 mm microjet. However, there is less shock wave magnitude and shockwave cells shown in the microjet due to the great viscous effect.

A study in the effects of a new calibration technique on the 2D flow parameters

11999
Thu·14:40·6

Mojtaba Manshadi,† Bavand Keshavarz, Kaveh Ghorbanian and Mohammad Soltani
Sharif University of Technology, Iran†

In this paper the authors introduce a new genetic algorithm based method for direct calibration of 2D flows. This new method is an alternative for the previous method proposed by Oster and Wygnanski (named in this paper as the QR method). Both methods were applied on a set of experimental hot-wire data from an X-probe hot-wire in a 2D flow and the proposed GA method resulted in a much smaller error in velocity estimation than the QR method. A considerable difference was also detected in the flow parameters including turbulence properties of the flow obtained from each way (QR or GA); indicating the effect of calibration equation on evaluating the 2D flow parameters.

Experimental study of lid driven cavity flow in the Lagrangian frame of reference

10591
Thu·14:45·6

Reut Elfassi† and Alexander Liberzon
Tel Aviv University, Israel†

Lid-driven cavity (LDC) flow is a classical example of a complex flow in confined domain. It is also ubiquitous in natural and industrial flow systems and extensively studied in two- and three-dimensional configurations both in experiment and in simulations. The three-dimensional aspects of the LDC flow are the main focus of our experimental study. Our aim is to capture the important physical aspects of LDC flows as a function of Reynolds number and different aspect ratios. Main experimental tool is the three-dimensional particle tracking velocimetry (3D-PTV), providing 3D pathlines of flow tracers in the Lagrangian viewpoint (following particle's motion in the flow), along with the fields of velocity, acceleration and spatial velocity derivatives (vorticity, rate-of-strain, etc.). Lagrangian investigation will shed more light on the transport and mixing properties of laminar and turbulent LDC flows.

Prediction of aerodynamic coefficients of a plunging airfoil using neural networks

11583
Thu·14:50·6

Feazeh Marzabadi,† Mehran Masdari and Mohammad Soltani
Sharif University of Technology, Iran†

The neural networks were used to minimize the amount of data required to predict the aerodynamic coefficients of an airfoil oscillating in plunging motion. For this purpose, series of experimental tests have been conducted on a section of a 660 kW wind turbine blade. Two MLP (multi layer perceptron) and GRNN (general regression) neural networks were trained using experimental data of the airfoil at various conditions. Results showed that with using only 50% of the acquired data, the trained neural networks were able to predict accurate results with minimal errors when compared with the corresponding measured values. Moreover, these methods can predict the aerodynamic coefficients of the plunging airfoil at the different oscillation frequencies, amplitudes, and incidence angles.

Optically interrogated MEMS pressure sensor array

11387
Fri·09:15·D

Lukas Prochazka† and Thomas Roesgen
ETH Zuerich, Switzerland†

The concept and design of a new passive and wireless pressure sensing system for wind tunnel application are presented. The technique is based on an imaging interferometer interrogating an array of silicon diaphragm microresonators (diaphragm thickness 6 μm). The small sensor size ($3 \times 3 \times 0.2$ mm) and the absence of any electrical interfacing facilitate a fast installation directly on the surface of the model. A capacitive ultrasound transducer excites the diaphragm into free oscillations from a distance of about 2 m. Dependent on their quasi static deflection caused by a pressure load the resonance frequency varies with an average pressure sensitivity of 3 Hz/Pa at 70 kHz. The resonance frequency of each individual sensor is recorded simultaneously by interferometric means using a highly sensitive "active-pixel" CMOS camera (full field lock-in detector). A maximum pressure and temporal resolution of 0.2% of FS (10 kPa) and 1 Hz are required.

Planar imaging measurements of molecular transport effects in turbulent mixing

11840
Fri·09:35·D

Lester Su† and Cody Brownell
Johns Hopkins University, USA†

Planar laser imaging yields quantitative measurements of gas-phase turbulent mixing with differential molecular diffusion. The flow studied is a binary jet mixture (helium-propane or helium-acetone) issuing into air. This paper describes two sets of experiments. The first employs Rayleigh scattering for direct measurements of a scalar variable that quantifies the differential diffusion. Measured spectra of the differential diffusion variable are at odds with analytical predictions, and suggest that isolated flow regions with low turbulence intensity have a disproportionate impact on the evolution of the differential diffusion field. The second set of experiments applies Rayleigh scattering and laser-induced fluorescence simultaneously, providing information on the mole fractions of the jet constituent species through an inversion process. These measurements allow examination of multi-species mixing in gas-phase jets in a way that has previously been practical only in the liquid phase.

An efficient correction for the finite-size effects of multihole pressure probes in velocity gradients

10383
Fri·09:55·D

Valery Chernoray† and Johan Hjärne
Chalmers University of Technology, Sweden†

This study describes an implementation and verification of an efficient and reliable correction for the finite-size effects of pressure probes. The performance of the correction in application to the highly three-dimensional flow downstream of the linear cascade is scrutinized through a detailed side-by-side comparison with corresponding cross hot-wire data. The influence of the correction on all three velocity components, flow streamlines and streamwise vorticity fields is thoroughly examined. The study demonstrates that the correction lead to a significant improvement of the velocity data. A very good performance of the correction for the finite-size effects of pressure probes presented in this study allow us to recommended it as a mandatory step in postprocessing procedures for multi-hole pressure probes.

10656
Fri·10:15·D

Measurements of the dynamic wall-shear stress distribution in turbulent flows using the micro-pillar sensor MPS^3

Sebastian Grosse† and Wolfgang Schröder
RWTH Aachen University, Germany†

A new sensor to measure the wall-shear stress distribution in turbulent flows at low to moderate Reynolds numbers is presented. The sensor consists of flexible micro-pillars which extend from the wall into the viscous sublayer. The static and dynamic calibration technique of the micro-pillar shear-stress sensor MPS^3 will be elucidated. Comprehensive findings from wall-shear stress measurements in turbulent pipe flow will be shown, evidencing the capability of the sensor technique to correctly detect the mean and dynamic wall-shear stress. Findings of the wall-shear stress distribution of turbulent duct flow evidence that regions of lower and higher wall-shear stresses coexist relating to very near-wall coherent structures. The structures have cigar-like shapes with spanwise extensions in the order of $20-30\ l^+$. Applying Taylor's hypothesis will allow to estimate the streamwise extension of the structures. The spectral densities indicate the length to be in the order of $1000\ l^+$.

11117
Fri·11:00·D

Heterodyne Doppler global velocimetry

Alexander Meier† and Thomas Rösgen
ETH Zurich, Switzerland†

Doppler Global Velocimerty (DGV) is a flow measurement techique which allows the measurement of the velocity in an imaging plane. In DGV the frequency shift of scattered light from moving particles within the flow is used to determine the local flow velocity. Heterodyne Doppler Global Velocimetry (HDGV) is a new approach to DGV. The frequency shifted scattered light from the flow tracers is heterodyned with a reference beam from the same light source. The result of this superposition is due to interference a harmonic intensity modulated signal. This signal is detected using a smart pixel imaging array to obtain the velocity distribution. Two different experiments are presented: The first experiment compares the measured velocity distribution of a rotating disk with its actual velocity. The second experiment shows the capability of the technique to measure a real flow.

12137
Fri·11:20·D

Large spatial dynamic range measurements of a turbulent boundary layer and the velocity gradient tensor using tomographic PIV

Craig Dillon-Gibbons,† Callum Atkinson and Julio Soria
Monash University, Australia†

A streamwise and wall-normal volumetric slice of a turbulent boundary layer ($\mathrm{Re}_\theta = 2200$) is measured using 2 stereo camera systems with a small overlap in the streamwise direction. Tomographic particle image velocimetry (Tomo-PIV) is used to reconstruct the three-dimensional particle distribution and provide three-component three-dimensional (3C-3D) velocity field data. The use of two high-resolution camera (4008×2672 px) stereo-systems enables a large in-plane field of view ($2.6\delta \times 0.75\delta$) and a high spatial resolution (PIV interrogation volume size 13.6^+). Tomo-PIV also provides measurements of multiple planes in the spanwise direction to a depth of 0.03δ, in this case corresponding to 3 independent planes. This enables estimation of the velocity gradient tensor A_{ij}, which is essential for most vortex identification and topology methodologies.

FM09 :: Flow control

Chairs: Avi Seifert (Israel) and Jonathan Morrison (UK)

Tue	14:40–14:50	Hall A	Seminars
Thu	16:00–17:00	Hall B	Lectures
Fri	11:00–12:20	Room 6	Lectures

Flow control by turbulence state modifications in the near-wall region

11064
Tue·14:40·A

Bettina Frohnapfel,† Peter Lammers, Yosuke Hasagawa and Nobuhide Kasagi
The University of Tokyo, Japan†

Significant drag reduction is obtained in numerical simulation of turbulent channel flow by forcing local turbulence in the near-wall layer to approach a one-component state, where only the streamwise velocity fluctuation remains. The drag reduction rate obtained with the modified layer of a thickness $y_d^+ \approx 5$ is in the order of 30%. This value is in agreement with the drag reduction rate estimated based on the FIK identity for a channel flow in which all turbulence has been suppressed in the near-wall layer. This fact suggests that the idealized damping of turbulence in the near-wall region, which has resulted in large drag reduction even at high Reynolds numbers, is achievable by a mere reorganization of turbulent fluctuations.

Optimization of the dynamic properties of compliant coating

11969
Tue·14:45·A

Inwon Lee,† Victor Kulik, Andrey Boiko and Ho Chun
Pusan National University, South Korea†

An improved method to measure the dynamic viscoelastic properties of elastomers is proposed in this study. The method is based on the analysis of forced oscillation of a cylindrical sample loaded with inertial mass. The problem of finding parameters of compliant coating providing close to optimal interaction with a turbulent flow becomes was advanced. To this end, the normal and longitudinal surface deformations of a flat layer of viscoelastic material glued onto a solid base were determined under the action of traveling pressure wave. Two components of the coating compliance are described by two components of the surface deformation. A specially designed flat plate was mounted vertically over the axial line in the wind tunnel of the Aerospace Department of the Pusan National University. The plate is 2 m long, 0.8 m high and 8 cm thick. The measurements were performed in velocity range from 15 to 30 m/s.

Estimation of the potential of a flow-control experiment by system identification

11787
Thu·16:00·B

Fredrik Lundell
Linné Flow Centre, Sweden

System identification is applied to data from an experiment in which the disturbance level was decreased by feedback control. The flow case is a laminar boundary layer under a turbulent free stream. The identified system makes it possible to estimate the disturbance attenuation for given sensor and control inputs to the identified system. First, it is shown that the experimental results are reproduced when the inputs are taken from the experimental data. Thus verified, the identified system is used to determine a more efficient control input. At the same control effort, the estimated control result is shown to be improved substantially. The mechanism behind this potential is that the step response from actuator to flow is non-monotonic.

Wake flow manipulation by means of blowing or suction **11810** Thu·16:20·B

Jens Fransson† and Bengt Fallenius
Linné Flow Centre, Sweden†

Recently, interest has been focussed on the ability to manipulate the wake of bluff bodies to reduce drag, increase heat transfer or mixing, and enhance combustion. In this experimental study the surface pressure distribution, vortex shedding frequency and the wake flow behind a circular porous cylinder are studied when continuous suction or blowing is applied through the cylinder wall. Smoke visualizations, hot-wire and PIV are used to retrieve qualitative as well as quantitative flow information. It is found that even moderate levels of suction/blowing have a large impact on the flow around the cylinder. Suction delays separation contributing to a narrower wake width, and a corresponding reduction in drag, whereas blowing shows the opposite behaviour. A Matlab program using a standard vortex detection algorithm has been developed for the PIV data, which provides statistical information about vortex sizes, strengths, location etc., when varying the suction/blowing rate.

Optimal control of vortex systems **11904** Thu·16:40·B

Bartosz Protas
McMaster University, Canada

This investigation is concerned with solution of optimal control problems for vortex systems using methods of the modern control theory. To fix attention we are interested in two-dimensional flows past circular obstacles in unbounded domains. Following a review of the relevant proprieties of equilibrium solutions of the Euler equation, we first describe the solution of the stabilization problem for the Föppl system using a linear feedback strategy. We prove that the controlled Föppl system exhibits a center manifold. In the second part of the presentation we discuss an optimal control problem for the Prandtl–Batchelor flows involving finite-area vortex regions. We emphasize the role played by the shape-differential calculus as a key enabler in characterizing the optimal solution in this problem. Our presentation will involve a combination of mathematical analysis and large-scale numerical computations.

Active control of flow with trapped vortices **10399** Fri·11:00·6

Owen Tutty,† Ruslan Kerimbekov and Eric Rogers
University of Southampton, UK†

Simulations using a Discrete Vortex Method have been performed for the flow past a airfoil with a cavity around the point of natural separation. The aim is to trap a vortex in a cavity in the airfoil in order to suppress separation. The base flow is highly unstable and some control mechanism is required to hold the vortex in the cavity. Open and closed loop control based on distributed surface suction has been investigated. A feasible efficient control strategy employing a mixture of feedback control to stabilise the flow followed by open loop oscillatory suction to hold the vortex in the cavity at a lower cost has been identified.

Dynamic roughness actuation of a turbulent boundary layer **11024** Fri·11:20·6

Beverley McKeon,† Jacob George and Jeffrey LeHew
California Institute of Technology, USA†

The use of a "dynamic roughness" to manipulate, interrogate and ultimately control a turbulent boundary layer is described, where the actuation corresponds to local or global changes to the morphology of a continuous actuating surface. The introduction, for the first time, of a roughness timescale alongside the distribution of roughness lengthscales associated with rough surfaces is investigated with a view to understanding the influence of this actuator, expanding on current understanding of static roughness effects. This method of actuation has the potential to be used either in an "on/off" configuration to selectively enhance local skin friction or, potentially, with time-dependent motion in order to maintain a particular optimized boundary layer state (with a long-range goal of skin friction reduction). The current work also seeks to enhance our understanding of turbulent boundary layer structure in order to address this latter application.

Synchronized force and PIV measurements on an electromagnetically forced separated flow

11600
Fri·11:40·6

Christian Cierpka,† Tom Weier and Gunter Gerbeth
Forschungszentrum Dresden-Rossendorf, Germany†

Periodic addition of momentum by wall-parallel electromagnetic forces has a strong influence on the separated region of a stalled airfoil. As in the case of periodic blowing and suction, actuation frequency, momentum input as well as the wave form are the main factors of influence. The controlled flow possesses typically a small number of relatively large vortices, which are believed to be related to the control mechanism. In the present paper synchronized force and time resolved particle image velocimetry measurements of the electromagnetically excited flow at a NACA 0015 ($\alpha = 20°$, $\mathrm{Re} = 1 \cdot 10^5$) will be presented. Continuous wavelet transform and phase averaging are used to extract dominant features of the flow and to make the direct link between lift and drag and the coherent structures.

Low-order estimation and modeling of transient growth in a laminar boundary layer

10498
Fri·12:00·6

Jonathan Morrison† and Ahmed Naguib
Imperial College London, UK†

Motivated by feedback control of bypass transition of boundary layers, we examine the suitability of proper orthogonal decomposition (POD) for use in the estimation and reduced-order modeling of transient growth in a laminar boundary layer. The study focuses on testing the observability of the POD modes and the ability to predict their temporal evolution through a reduced-order, dynamical model. It is found that the leading POD mode of the wall-normal velocity fluctuation is observable from surface shear stress measurements. Moreover, the amplitude of this mode is accurately predicted using a Galerkin, reduced-order dynamical model. Overall, the results suggest that a POD-based framework is quite promising for implementation of feedback control of boundary layer transition. It is important, however, to also investigate the controllability of the POD modes for comprehensive assessment of the framework.

FM10 :: Flow instability and transition

Chairs: Jean-Marc Chomaz (France) and Dan Henningson (Sweden)

Mon	14:00–16:00	Hall B	Lectures
Tue	10:40–12:40	Room 5	Lectures
Thu	11:00–13:00	Hall A	Lectures
Thu	14:00–15:00	Room 3	Seminars
Fri	09:15–10:35	Hall A	Lectures
Fri	11:00–12:20	Hall A	Lectures

The inviscid Rayleigh–Taylor instability **10772**
Mon·14:00·B

Larry Forbes
University of Tasmania, Australia

Rayleigh–Taylor flows occur when a heavy fluid overlies a light one. Waves at the interface between the fluids are then unstable, and grow with time. Sir G.I. Taylor presented a famous linearized solution for inviscid fluids. It showed that the growth rate depends on wavenumber and density ratio. Here, non-linear solutions are computed to the inviscid problem, using a novel spectral method. They show the growth of interfacial waves, and confirm that a Moore curvature singularity develops there within finite time. In addition, over-hanging portions can form at the interface.

A new instability in thermal boundary layers **11260**
Mon·14:20·B

Jianjun Tao[†] and Friedrich Busse
Peking University, China[†]

The thermal boundary layer around an inclined plate heated in a thermally stratified fluid is investigated and a novel oblique roll (OR) instability is identified. One character of the OR mode is: it has smaller critical Grashof number than the TS wave at proper tilt angle for some fluids. This feature is surprising because the transverse TS wave has been reported as the most unstable normal mode for infinitesimal disturbances in boundary-layer flows. In comparison with TS waves, Oblique rolls have lower critical frequencies and lower critical streamwise wavenumbers. Another important feature of the OR mode is that its amplitude decreases more slowly with distance from the plate than the amplitude of stationary longitudinal rolls and TS waves. As a result, OR temperature disturbances penetrate into the stably stratified region two times deeper than TS waves. In fact the oblique rolls appear to be caused by resonating internal waves.

Wake structures behind a rolling sphere on a wall **11352**
Mon·14:40·B

Bronwyn Stewart,[†] Thomas Leweke, Mark Thompson and Kerry Hourigan
Monash University, Australia[†]

Flow visualizations are presented for the wake behind a spherical body moving along a plane wall in the Reynolds number range $100 < Re < 350$. Five different rotation rates are examined and as the sphere undergoes forward rolling, the observed wake modes bear similarities to the flow behind an isolated sphere in a free-stream. For cases with reversed and zero rotation of the sphere, a new anti-symmetric wake mode is observed.

Computation of convective instability in complex geometry flows **10291** Mon·15:00·B

Hugh Blackburn,† Dwight Barkley and Spencer Sherwin
Monash University, Australia†

We describe and apply a methodology for the computation of optimal linear disturbances to flows in arbitrary geometries. The treatment uses primitive flow variables and is based on sequential time integration of the linearised Navier–Stokes equations and their adjoint. We demonstrate the correspondence between the singular value decomposition of the linearised Navier–Stokes operator and the optimal growth initial condition, its outcome, and the associated energy growth. Inherently, the method provides a means of computing optimal disturbances for flows that contain regions of local convective instability.

Effect of surface roughness on the laminar–turbulent transition in channel flow **10368** Mon·15:20·B

Jerzy Floryan† and Masahito Asai
University of Western Ontario, Canada†

The question of whether a system of roughness elements has to be viewed either as a distributed roughness or a set of individual, hydrodynamically independent roughness elements has been considered. The answer has been given in the context of definition of hydraulic smoothness where a wall with a roughness system that cannot destabilize the flow is viewed as “hydraulically smooth”. Stability characteristics have been traced from the distributed to the isolated roughness limits. It has been shown that an increase of distance between roughness elements very quickly stabilizes disturbances in the form of streamwise vortices but coupling with disturbances in the form of traveling waves persists over long distances. The transition to the isolated roughness limit is achieved much faster in the case of roughness elements in the form of “ridges” rather then “trenches”. The available experimental results confirm theoretical predictions.

Secondary instability of variable-density jets **10499** Mon·15:40·B

Jean-Marc Chomaz,† Joseph Nichols and Peter Schmid
Centre National de la Recherche Scientifique École Polytechnique, Palaiseau, France†

Side jet formation in variable density jets is studied by means of numerical simulation and linear stability analysis. A jet containing a global axisymmetric primary instability is found also to be unstable with respect to secondary global modes. The secondary linear system is demonstrated to be highly non-normal suggesting that side jets may be explained by a competition between global modes and transient response.

Convective and absolute instability of two miscible fluid core-annular flow

10372
Tue·10:40·5

Dominique Salin,† Nicole Rakotomalala, Jerome Martin, Marguerite d'Olce and Laurent Talon
Universite Pierre & Marie Curie, France†

To address the issue of the convective or absolute nature of the instability of core annular flows in a pipe, we report on experiments with two miscible fluids of equal density but different viscosities. The fluids were injected co-currently and concentrically into a cylindrical pipe. The resulting base state is an axisymmetric parallel flow. For a given viscosity ratio, the two experimental control parameters are the total flow rate of the two fluids which monitors the Reynolds number Re whereas the ratio of the two fluid flow rates leads to the relative radius of the core fluid R_I, under condition of parallel flow. In the space of these two parameters, we characterize experimentally the convective or absolute nature of the instability and delineate the transition between absolute and convective instability.

Transition to turbulence in a pipe

10578
Tue·11:00·5

Tom Mullin
University of Manchester, UK

The puzzle of why fluid motion along a pipe is observed to become turbulent as the flow rate is increased remains the outstanding challenge of hydrodynamic stability theory, despite more than a century of research. The issue is both of deep scientific and engineering interest since most pipe flows are turbulent in practice even at modest flow rates. All theoretical work indicates that the flow is linearly stable i.e. infinitesimal disturbances decay as they propagate along the pipe and the flow will remain laminar. Finite amplitude perturbations are responsible for triggering turbulence and these become more important as the non-dimensionalized flow rate, the Reynolds number Re, increases. We will show that there are several scalings with Re of the amplitude of the perturbations required to cause transition. Each of these gives insights into origins of the turbulent motion and provide links with recent theoretical and numerical work.

Transitional plane Couette flow: an alternative to the low-dimensional dynamical system approach

10880
Tue·11:20·5

Paul Manneville
Ecole Polytechnique, France

Poiseuille pipe flow (Ppf) and plane Couette flow (pCf), both lacking linear instability modes, become turbulent through the nucleation and growth or decay of turbulent domains that have been interpreted within the framework of low dimensional dynamical systems theory as transient chaotic states associated to stochastic repellors. But limitations due to finite observation times and/or system size may play a role and correlative spatiotemporal processes cannot be ruled out in the transitional regime. In the pCf case, the problem has been explored via numerical simulations of a model focusing on the in-plane (x, z) space dependence of a few velocity amplitudes with reduced cross-stream (y) dependence. The model appears well suited to the study of the low-R transitional range. I shall present my most recent findings, discuss them in view of obtained those for Ppf, and attempt to make a connection with the theory of first order phase transitions proposed long ago by Pomeau.

The strato-rotational instability with and without boundaries: application to Keplerian flows

11197
Tue·11:40·5

Stéphane Le Dizès
Centre National de la Recherche Scientifique, France

The linear inviscid stability of a centrifugally stable family of rotating flows in a linearly stratified fluid is analysed using numerical and asymptotic methods. The azimuthal velocity of the rotating flow is given by $V = A/r + (1 - A)/r^{1/2}$ for a radial coordinate between $r = 1$ (inner boundary) and $r = d > 1$ (outer boundary, or without boundary if $d = \infty$). The stability properties are obtained for flow parameters between $A = 1$ (potential flow) and $A = 0$ (pure Keplerian flow), for several d and Brunt-Väisälä frequency N. The asymptotic results, which are obtained by a WKBJ approach for large perturbation axial wavenumbers, provide an explanation in terms of internal wave resonance when two boundaries are present and unstable wave emission without external boundary. Whatever A and d, the flow is found to be unstable if strongly stratified ($N > 1$).

Global low-frequency oscillations in a separated boundary layer

11226
Tue·12:00·5

Francois Gallaire† and Uwe Ehrenstein
Laboratoire J.-A. Dieudonné, France†

In the aim of shedding new light on the phenomenon of global 'flapping' in separated wall-bounded flows, the two-dimensional flow over a bump is considered. Unstable nonlinear equilibrium states of the Navier–Stokes system are determined using of a continuation procedure. A global linear instability analysis of these states is then performed. The loss of stability of this separated flow is associated with a set of localized global modes becoming simultaneously unstable. While the structures of these modes are similar, their frequencies differ but are equally spaced. The dynamics resulting from the superposition of these non-normal modes gives rise to a low-frequency beating associated to a periodic regeneration of the resulting perturbation. This has been confirmed by the time-integration of the nonlinear Navier–Stokes equations: the frequency spectrum displays a low-frequency peak, centered at frequency gap between the modes.

Instability of steady and pulsatile flow in stenotic geometries

11717
Tue·12:20·5

Martin Griffith,† Thomas Leweke, Mark Thompson and Kerry Hourigan
Monash University, Australia†

A numerical and experimental investigation of steady and pulsatile flows through a tube partially obstructed by an axisymmetric blockage is presented. The geometry serves as an idealised model of an arterial stenosis. The pulsatile flow consists of a steady downstream flow with a single-harmonic sinusoidally varying oscillation. Comparisons are made between the numerical and experimental results, with a focus on the limits of stability. For both steady and pulsatile flows, linear absolute instabilities and critical Reynolds numbers are found numerically, although the experimental flows are found to be convectively unstable for much lower Reynolds numbers.

Transition control in swept-wing boundary layers **11771** Thu·11:00·A

William Saric,† Andrew Carpenter and Helen Reed
Texas A&M University, USA†

Boundary-layer transition in flight is measured using infra-red thermography and hotfilm anemometry. Roughness-related issues are studied on a swept-wing model that is mounted on the wing of an aircraft. A Navier–Stokes code is used calculate the aircraft flowfield and boundary layer while Nonlinear Parabolized Stability Equations quantify the stability measurements and transition locations. The laminarization scheme of spanwise-periodic distributed roughness elements (DRE) is investigated at chord Reynolds numbers of 8 million. Measurements were made to determine the transition locations for clean configurations and for enhanced surface roughness that simulates an operational surface finish. For clean configurations, natural laminar flow was achieved over 80% of the surface of a 37? swept-wing model at chord Reynolds numbers of 8.1 million. With a surface roughness of 1 micron, transition moved forward to 30% chord. The DRE delayed transition to 60% chord.

Symmetry breaking in two-dimensional, diverging-channel flow **11777** Thu·11:20·A

Philip Haines,† Richard Hewitt and Andrew Hazel
The University of Manchester, UK†

We present finite-element calculations for the flow of an incompressible Newtonian fluid in a (finite) two-dimensional diverging channel and compare the results to the Jeffrey–Hamel similarity solution for a number of wall-separation angles 2α, Reynolds numbers Re and ratios of inlet/outlet radii, Γ. We solve the two-dimensional eigenvalue problem and apply continuation methods to find a set of nested neutral curves in the $Re-\alpha$ plane that correspond to symmetry breaking (about the mid plane of the channel). The first bifurcation is found at parameter values that are close to those predicted by the similarity solution, but (in general) the bifurcation has a different criticality (supercritical rather than subcritical). We discuss this somewhat surprising result, but also demonstrate that there is a (rather specialised) class of inlet conditions for which subcritical behaviour can be achieved.

Experiments on the elliptic instability in vortex pairs with axial core flow **10122** Thu·11:40·A

Thomas Leweke,† Clément Roy, Thomas Leweke, Mark Thompson and Kerry Hourigan
Centre National de la Recherche Scientifique, France†

We show experimental results concerning the interaction of two parallel counter-rotating vortices presenting a jet-like axial velocity profile in their cores. The vortex pair is generated by two wings in a water channel; it is visualized by dye injection, and characterized quantitatively by stereoscopic Particle Image Velocimetry. Two types of three-dimensional instability are observed: the long-wavelength Crow instability and a short-wavelength core instability caused by the mutually induced elliptic deformation of the vortex streamlines. We here focus on the short-wave (elliptic) instability, for which we deduce the perturbation mode structure, which is different from the one observed without axial flow, the axial wavelength and the growth rate from the experimental data. Comparisons are made with the results from a numerical linear stability analysis of the measured flow, and good overall agreement is found.

Interactions between wave motions and a spanwise array of streamwise streaks

10722
Thu·12:00·A

Jonathan Watmuff
RMIT University, Australia

A zither of fine wires located upstream of the leading edge of a flat plate generates a spanwise array of laminar wakes which interact with the leading edge to form a spanwise array of large amplitude spanwise thickness variations in the Blasius boundary layer forming on the plate. Each region of elevated layer thickness is equivalent to a long narrow low-speed streak. A uniform spanwise wire spacing of 12.7 mm generates local rms TS amplitude and background unsteadiness in the vicinity of each streak which is much the same as those observed for an isolated streak by Watmuff (2006). At this particular streamwise position the streak spacing is twice the boundary layer thickness. The behaviour for large streak spacings is almost identical to behaviour introduced by an isolated streak. Placing two additional wires in the zither leads to a streak spacing which is almost exactly equal to the layer thickness. The closer streak spacing is responsible for suppressing the breakdown of TS waves.

Sensitivity and forcing response in separated boundary-layer flow

10169
Thu·12:20·A

Jean-Christophe Robinet,[†] Stefania Cherubini, Frédéric Alizard and Pietro De Palma
SINUMEF Laboratory, France[†]

The stability of separating boundary-layer flow on a flat plate is numerically investigated by means of three-dimensional eigenmodes of the linearized Navier–Stokes equations obtained by linearization about the steady state. By expanding the flow disturbance variables in the basis of eigenmodes the growth potential is revealed by the computation of the optimal initial condition. This yields a low-dimensional model of the flow and a unified view on its stability characteristics. Furthermore, a general formalism is developed to assess how harmonic forcing may alter the stability properties of flows studied by a global approach of the linear stability theory. This formalism is based on the sensitivity analysis performed by the pseudo-spectrum calculation and the resolution of the forced problem. These results are compared and extended with direct numerical simulations.

Optimal perturbation in a channel flow: adjoint-based and Riccati-based control comparison

11629
Thu·12:40·A

Patricia Cathalifaud,[†] Laia Moret-Gabarro and Christophe Airiau
Institut de Mécanique des Fluides, France[†]

Active open-loop and closed- loop control of optimal instabilities amplified in a channel flow is investigated. The control is carried out at both the upper and the lower wall by blowing and suction. The state system considered is parabolic in time. We used both adjoint-based and Riccati-based control theories. In the adjoint-based method, we alternatively solve the state (forward time marching) and the adjoint (backward time marching) systems until convergence towards the optimal control. In the feedback control method, the control is the solution of a differential Riccati equation which marches in time. We show that the adjoint-based (open-loop) and the Riccati-based (closed-loop) control results are very similar, which is interesting since Riccati-based control may be difficult to implement for high-dimensionnal systems such as flow systems.

Biglobal stability analysis of an unsteady separated flow with wall curvature

10276
Thu·14:00·3

Julio Soria,† Vassili Kitsios, Vassilis Theofilis, Andrew Ooi and Daniel Rodriguez
Monash University, Australia†

A BiGlobal stability analysis of an instance of unsteady laminar separation is presented. The most appropriate forcing frequency to initiate flow reattachment is determined. The flow configuration is an airfoil at an angle of attack where laminar separation occurs at the leading edge. A zero-net-mass-flux jet, normal to the surface and spanning the entire leading edge provides the perturbation. The uncontrolled flow is numerically generated using a three-dimensional Large Eddy Simulation (LES) and agrees well with PIV and force measurements of complimentary water tunnel experiments. The stability analysis is undertaken on the LES mean velocity field. A series of co-ordinate transformations are undertaken to transform the airfoil geometry to an equivalent flat plate, and the stability analysis performed in this flat plate space. The frequency determined from the stability analysis is compared to the forcing frequency that maximised lift enhancement in the experiments.

On investigation of sinusoidal and varicose instabilities of streaks in boundary layers

10303
Thu·14:05·3

Victor Kozlov,† Valery Chernoray and Lennart Loefdahl
Institute of Theoretical and Applied Mechanics, Russia†

Experimental studies of nonlinear instabilities of boundary layer streaks are discussed. Extensive measurements visualizing the sinusoidal and varicose instabilities of streaks at nonlinear stages of breakdown process are presented. Specific features of the development of the streamwise streak breakdown are demonstrated, and various scenarios of the origination and development of coherent vortex structures are discussed. Furthermore, experimental studies on the breakdown of boundary layer streaks at adverse pressure gradient under fully controlled experimental conditions are presented. The varicose mode of streak breakdown is found to be a dominant mode in this case. A strong influence of pressure gradient upon the development of streak and secondary instability is revealed. The pressure gradient is shown to alter the critical streak amplitude, the dispersion properties of streak and secondary disturbance, and attained maximum amplitudes for both streak and secondary disturbance.

An experimental and numerical study of the Faraday instability with miscible liquids

10505
Thu·14:10·3

Sakir Amiroudine,† Ranga Narayanan and Farzam Zoueshtiagh
Ecole Nationale Supérieure d'Arts et Métiers, France†

We present a study on the Faraday instability with two miscible liquids of different densities. Our study comprises of an experiment where a container with the fluids is subject to mechanical oscillations leading to a Faraday instability of the miscible 'interface'. We present definitive experiments in a Hele–Shaw geometry with two systems. The first system consists of silicone oils while the second consists of brine and pure water. The frequency of oscillations range from 0.5 to 10 Hz and the amplitude varies from 0.5 to 10 cm. The instability is manifested by a wave generation at the diffuse interface and is recorded by a high speed camera. Calculations using a full nonlinear finite volume code for a Newtonian, Boussinesq fluid is in very good agreement with the experiment. Our talk will focus on the physical explanation for instability appearing in the results. Future experiments will also be outlined.

Relaxation approach for stable PSE integration **11113** Thu·14:15·3

Seung Park† and Bing Gao
Korea Advanced Institute of Science and Technology, South Korea†

It is well known that a conventional marching scheme of the parabolized stability equation (PSE) suffers a step size limit problem in that the marching step size should be greater than a specific value for stable calculation, which is obviously undesirable. A couple of ways to alleviate this step size limit have been proposed. In the present work, we propose a spatial relaxation technique to overcome the step size limit problem where very small step size can be taken without numerical instability. A one-step relaxation scheme and a two-step predictor-corrector type scheme for better accuracy are proposed. Numerical examples demonstrate that the proposed schemes are robust and accurate.

Three-dimensional Richtmyer–Meshkov instability and turbulent mixing of a gas/liquid interface **11136** Thu·14:20·3

Hong-Hui Shi† and Qi-Wei Zhuo
Zhejiang Sci-Tech University, China†

This paper presents an experimental investigation on the three-dimensional Richtmyer-Meshkov (RM) instability and turbulent mixing phenomena at a gas/liquid interface. The experiment was conducted in a vertical rectangular shock tube which has an inner dimension of 35 mm times 35 mm. Different tests with shock wave Mach number of 1.36, 1.50 and 1.58 were tested. The later development of the RM instability and subsequent phenomenon were recorded by a CCD camera. The related parameters such as the spike and bubble heights as well as the width of the mixing region were measured. A discussion to the experimental events has been made.

Low frequency instabilities in the initial merging zone of an annular jet **11237** Thu·14:25·3

Maarten Vanierschot† and Eric van den Bulck
Katholieke Universiteit Leuven, Belgium†

This papers investigates the flow structure in the wake behind the centrebody of an annular jet using time-resolved stereoscopic PIV (TR-SPIV) measurements. The wake consists of an asymmetric toroidal vortex (TV), which closes downstream at the stagnation point. The axis of this TV is tilted with respect to the central axis of the geometry and precesses around it, corresponding to a Strouhal number of 4.7×10^{-3}. This low frequency instability creates a highly 3 dimensional flow field. For instance near the stagnation point, up to 25% of the rms velocity fluctuations are attributed to it. By the authors knowledge this kind of precession is not yet reported in the literature (direct or indirect), since the known Strouhal numbers of the instabilities (due to vortex shedding) in these kind of flows are much higher.

Linear stability analysis of secondary instability of boundary layer flow on a two-dimensional airfoil **11538** Thu·14:30·3

Takashi Atobe,† Jun Hiyama, Takahiro Sumi and Takuji Kurotaki
Japan Aerospace Exploration Agency, Japan†

Secondary instability of boundary layer flow on a two 2D airfoil is investigated by linear stability analysis using velocity profiles which are obtained by an advanced LES developed by the authors. The purpose of the present study is to elucidate a three-dimensional structure of which type is dominant in the secondary instability of the boundary layer in the presence of streamwise pressure gradient on the airfoil. For this, the Orr–Sommerfeld equation is employed for linear stability analysis. It is found that frequency of the unstable wave owing to the secondary instability is the half of one of the primary Tollmien–Schlichting (TS) wave, and spanwise wavenumber is smaller than the streamwise one of the TS wave. Thus it can be concluded that the type of the secondary instability occurring at the boundary layer flow on an airfoil is classified as the subharmonic instability, which belongs to the C-type.

Instabilities in bluff plate boundary layers **12117** Thu·14:35·3

Mark Thompson† and Hemant Chaurasia
Monash University, Australia†

A detailed numerical study of the boundary layer flow over a (semi-infinite) square leading-edge plate is presented, examining the instability modes which govern transition from two- to three-dimensional flow. While similar studies have been performed for circular cylinder wakes, there is evidence that flow instability modes may differ significantly for alternative geometries. We use a high-order spectral element code to conduct 2D simulations, Floquet stability analysis and 3D simulations of the flow, revealing a dominant instability mode with a similar perturbation field structure to the downstream Mode A instability structure of a circular cylinder wake. The instability is found to have a spanwise perturbation wavelength of 4.6H, in qualitative agreement with published experimental results. Indeed, the spatial structure of this instability is consistent with the generic elliptical instability mechanism, providing further evidence for its broad significance to flow transition.

Electrohydrodynamic instability in a horizontal Poiseuille flow with an electrical conductivity gradient **11571** Thu·14:40·3

Min-Hsing Chang,† An-Cheng Ruo, Falin Chen and Zhi-Wen Xiao
Tatung University, Taiwan†

The electrohydrodynamic instability in a thin fluid layer between two parallel plates is investigated with a vertical electrical conductivity gradient and a superimposed horizontal Poiseuille flow. A linear stability analysis is performed to explore the interaction between the unstably stratification of electric conductivity under an applied electric field and the shear instability. The superimposed shear flow is weak with small Reynolds number and both the longitudinal mode and transverse mode relative to the direction of shear flow are considered. The results show that the stability characteristics of longitudinal mode are independent of the superimposed Poiseuille flow, while the transverse mode appears to be stabilized by the shear flow. Particularly, the onset of instability is found to be dominated by the transverse mode as the conductivity gradient is lower than a certain critical value. The results benefit the understanding of low Reynolds number flows in microchannels.

Conditionally-sampled velocity in an oscillating-triangular-jet nozzle **11218** Thu·14:45·3

Peter Lanspeary,† Soon-Kong Lee and Peter Kalt
The University of Adelaide, Australia†

Equilateral triangular jet flow through a short cylindrical chamber may have strong precession-like oscillation, or for a very narrow range of chamber lengths, the jet may be deflected and stationary. Conditionally-sampled PIV confirms that, in both oscillating and stationary flows, there is strong swirl around the inlet jet and the inlet jet is deflected towards the wall of the chamber. Streamlines in cross sections of the chamber show that interaction between the swirl and the inlet jet produces streamwise vortices which are distributed along the chamber. Streamlines also show evidence of a vortex rising from each of two sink foci on the chamber surface. Inside the chamber, differences between the stationary-jet flow field and the oscillating-jet flow field are indistinct. In the external flow the difference is much clearer. The external stationary-jet flow consists of a pair of counter-rotating streamwise vortices, but these vortices are not detected in the oscillating-jet flow.

Stability of plane Poiseuille flow of a fluid with pressure-dependent viscosity

11062
Thu·14:50·3

Thien Tran[†] and Sergey Suslov
Vietnamese Academy of Science and Technology and University of Southern Queensland, Vietnam[†]

In the present conceptual study we investigate stability of plane Poiseuille flow of an incompressible fluid whose viscosity depends linearly on the pressure. We show that the critical Reynolds number for the onset of instability is a sensitive function of the applied pressure gradient. In contrast to its Newtonian counterpart piezo-viscous Poiseuille flow stabilises when the pressure gradient is increased. At the same time the flow in a sufficiently long channel becomes unstable regardless of the inlet conditions. This effect is not found for fluids with pressure-independent viscosity either. Inspite of these drastic differences from conventional flows we show that at small pressure gradients the local stability characteristics of piezo-viscous flows are remarkably similar to those of simple Newtonian flows. This suggests that common fluids could be considered as a low-pressure limit of fluids with a more complicated pressure-dependent rheology.

Vortex structure in an oscillating-triangular-jet nozzle

11782
Thu·14:55·3

Soon-Kong Lee,[†] Peter Lanspeary and Peter Kalt
The University of Adelaide, Australia[†]

Equilateral triangular jet flow through a cylindrical chamber may have strong precession-like oscillation, or for a very narrow range of chamber lengths, the jet may be deflected and stationary. In both oscillating and stationary-jet flows, there is a strong swirl around the jet near the inlet and there is a strong sink focus on the wall of the chamber. A vortex rises from the sink focus. Interaction between the swirl and the jet flow from the inlet orifice forms concentrated co-rotating streamwise vortex cores. These merge into a single vortex as they are advected through the chamber by the jet flow. The extent to which vortex structure is contained within the nozzle distinguishes between the stationary and the oscillating flows. In the oscillating flow, the vortex produced by the swirl and the vortex rising from the sink focus are connected to form a loop inside the chamber. If the loop breaks or more than about 35% of vortex circulation leaves the chamber, oscillation stops.

Flow destabilization and chaotic mixing in the channel with transversely corrugated walls

11606
Fri·09:15·A

Slawomir Blonski,[†] Tomasz Kowalewski and Jacek Szumbarski
Institute of Fundamental Technological Research, Poland[†]

Problem of mixing enhancement a viscous incompressible flow in a channel with wavy walls is investigated theoretically and numerically. The wall waviness is unidirectional and it is oriented spanwise, i.e., the lines of constant elevation are parallel to the driving pressure gradient. It is shown that appropriately chosen wall waviness leads to destabilization at surprisingly low Reynolds numbers. The linear stability analysis shows that the critical Reynolds number can be reduced even under 60, i.e., by two orders of magnitude when compared to the Poiseuille flow between flat parallel planes. The unstable mode of disturbances has the form of a vortex array, which travels downstream. The remarkable feature is that the most destabilizing waviness does not introduce any additional flow resistance. The results of the stability analysis are consistent with the result of direct numerical simulation performed using the finite volume CFD package Fluent.

Dynamics of a fluid inside a precessing cylinder

11817
Fri·09:35·A

Romain Lagrange,† François Nadal, Christophe Eloy and Patrice Meunier
IRPHE, CNRS and Aix-Marseille Université, France†

The instability of a fluid inside a precessing cylinder is studied theoretically and experimentally. This study is motivated by aeronautics and geophysics applications. Precessional motion forces hydrodynamics waves called Kelvin modes whose structure and amplitude are predicted by a linear inviscid theory. When a forced Kelvin mode is resonant, a viscous and weakly nonlinear theory has been developed to predict its saturated amplitude. We show that this amplitude scales as $Re^{1/2}$ for low Reynolds numbers and as $\theta^{1/3}$ (where θ is the precessing angle) for high Reynolds numbers. These scalings are confirmed by PIV measurements. For Reynolds numbers sufficiently large, this forced flow becomes unstable. A linear stability analysis based on a triadic resonance between a forced Kelvin mode and two free modes has been carried out. The precessing angle for which the flow becomes unstable is predicted and compared successfully to experimental measurements.

Primary and secondary instability of the boundary layer in a rotating annulus

11141
Fri·09:55·A

Bertrand Viaud,† Jean-Marc Chomaz, Eric Serre and Bertrand Viaud
French Air Force, France†

The present work aims at demonstrating the sustained existence of a steep-fronted nonlinear global mode (socalled elephant mode) in the case of a specific rotating-disk boundary layer, together with the subcritical nature of the associated global bifurcation.
The over-arching frame is the study of a possible direct route toward spatio-temporal disorder through secondary absolute instability, which would be consistent with the fact that in the experiments transition to turbulence is accounted for at a fixed Reynolds number with a very small scatter. In this prospect spectral Direct Numerical Simulation (DNS) has been applied to the flow between two co-rotating disks, with forced inflow and free outflow. The results, which match the theoretical description of an elephant mode, are coherent with a subcritical global bifurcation. Moreover, ongoing intensive computations give insights about the stability of this global mode with regard to secondary perturbations.

Poincaré section analysis of an experimental frequency intermittency in an open cavity flow

11329
Fri·10:15·A

François Lusseyran,† Christophe Letellier, Thierry Faure and Luc Pastur
LIMSI, CNRS, France†

Open flows over a cavity present, even at medium Reynolds number, sustained oscillations resulting from a complex feedback process, which remains to characterize from a dynamical point of view. An intermittency between the two dominant modes is characterized using a symbolic dynamics based approach. The first step of the procedure is to reconstruct the phase space from the time series measured by LDV technique, using the principal components. We show that the quite high dimensionality of the reconstructed space ($d < 10$), can be overcome by using a Poincaré section of the 2D projection of the phase portrait. The key step consists of a partition of the Poincaré section. The two modes are thus labelled 0 and 1, respectively. The partition is based on an angular map, itself based on a first-return map to the Poincaré section. This partition allows, without any arbitrary thresholding (as spectral based modes separation method needs), a very precise quantification of all oscillating events.

Symmetry breakings in the wake of a disk: a global stability analysis
11843
Fri·11:00·A

Philippe Meliga,[†] Jean-Marc Chomaz and Denis Sipp
ONERA, France[†]

The wake past an axisymmetric flat disk is investigated numerically. We use the framework of global stability to clarify the connection between the bifurcations undergone respectively by the axisymmetric steady state and the real flow. A model based on the normal form theory is presented. This model undergoes three successive bifurcations. The first bifurcation breaks the axisymmetry but preserves the time invariance, leading to a 3D steady state with a reflectional symmetry. A second Hopf bifurcation breaks both the time invariance and the remaining reflectional symmetry, leading to a fully 3D periodic state. A third bifurcation occurs then, where the flow remains unsteady, but recovers a lost reflectional symmetry. The dynamics and symmetry properties of the model stable solutions shows good agreement with that found by means of direct numerical simulations.

Spatial optimal disturbances in swept attachment-line boundary layers
12061
Fri·11:20·A

Patrick Huerre,[†] Peter Schmid and Alan Guegan
Ecole Polytechnique, France[†]

Spatial optimal disturbances taking the shape of spanwise vortices are computed for the swept attachment-line boundary layer near the leading edge of a swept wing. These vortices develop into spanwise streaks via the lift-up mechanism extracting a significant amount of energy from the basic flow. Analogous to classical boundary layers, this mechanism is most dominant for steady perturbations. The computations have been performed using an iterative direct-adjoint approach based on the Navier–Stokes equations parabolized in the chordwise coordinate direction.

Spatial-temporal stability of mixed forced-free convection boundary layers
11569
Fri·11:40·A

Eunice Mureithi[†] and Jim Denier
University of Pretoria, South Africa[†]

Spatio-temporal inviscid instability of a mixed convection boundary layer is investigated. The boundary layers considered exhibit internal regions where the streamwise velocity "overshoot" its free-stream value. A linear stability analysis has shown that spatial and absolute instabilities increases with increase in the buoyancy parameter G_0. A critical value for the buoyancy parameter, $G_0 = G_{0c} \approx 3.6896$, has been determined below which the flow is convectively unstable and above which the flow becomes absolutely unstable. Regions with higher "supervelocities" are more prone to absolute instability. At lower frequencies, a "long wave" instability sets in characterized by very small wavenumber. For $G_0 < G_{0c}$ this wave has much smaller spatial growth rate in comparison to the case when $G_0 > G_{0c}$.

On the instability of vortices embedded in shear flows

11990
Fri·12:00·A

Philip Hall
Imperial College London, UK

Streamwise vortices play a crucial role in the transition to turbulence of shear flows. The vortices can be produced by a variety of instability mechanisms or induced directly by forcing from other sources such as wall imperfections. It is known that either sinuous or varicose modes of instability of the vortices can occur and we show how they are related to the particular type of vortex/shear flow under consideration. It is shown that one mode preferentially occurs away from boundaries whilst the other one is localized away from boundaries. The role of arbitrarily small vortices in the destabilization of otherwise stable shear flows is discussed and applications of our results to flows of practical importance are given.

FM11 :: Flow in thin films

Chairs: Serafim Kalliadasis (UK) and Leonard Schwartz (USA)

Tue	16:00–17:40	Hall E	Lectures
Thu	09:15–10:35	Room 1	Lectures
Thu	16:00–17:00	Room 1	Lectures
Fri	09:15–10:15	Room 6	Lectures

Thin film flows over real surfaces

11851
Tue·16:00·E

Yeaw Lee,† Philip Gaskell and Harvey Thompson
University of Leeds, UK†

The challenging problem of the flow of thin liquid films over real surfaces is considered, containing large regions of interconnected micro-scale topography that form either man-made or naturally occurring functional surfaces. In addition the surfaces concerned can be either rigid or flexible as in the case of flow over thin membranes. Both situations are modelled in terms of lubrication theory and the associated equation set solved using a state-of-the-art highly efficient and accurate mutigrid methodology, embodying spatial and temporal error control facilitating automatic mesh adaptation and optimum time integration as the solution proceeds. A series of new results are presented relating to the flow over (i) leaf surfaces where evaporation is extremely influential and (ii) flexible membranes which can act as scaffolding for potential cell deposition and tissue growth; the two being examples of surfaces with randomly and regularly distributed topographical features, respectively.

Interfacial turbulence in falling liquid films

10518
Tue·16:20·E

Serafim Kalliadasis,† Sergey Vlaskin, Eugene Kalaidin and Eugene Demekhin
Imperial College London, UK†

The evolution of naturally excited disturbances on a thin liquid film falling down an inclined planar substrate undergoes several transitions between different wave regimes starting from two-dimensional (2D) solitary pulses at small Reynolds numbers to the ‘interfacial turbulence’ stage for sufficiently large Reynolds numbers where the interface is randomly covered by localized three-dimensional (3D) coherent structures. We analyze the instability of 2D pulses to 3D disturbances and the transitions of 2D pulses to fully developed 3D ones. We also construct bifurcation diagrams for 3D pulses as a function of the generalized Reynolds number δ and we examine their linear stability with respect to 3D disturbances. It is shown that the operator of the linearized system has both a discrete and an essential spectrum. The discrete spectrum is always stable while the essential spectrum can be destabilized leading to a convective instability of 3D pulses.

A general free surface rule for Stokes flow of fluid films over obstacles

11482
Tue·16:40·E

Markus Scholle,† Nuri Aksel, Harvey Thompson, Mark Wilson and Philip Gaskell
University of Bayreuth, Germany†

For gravity-driven Stokes flow of films on an inclined wall we derive a general rule for the film surface if the film passes a local irregularity of the wall, like a single obstacle or a trench. Starting from an exact solution of Stokes’ equations with complex functions, we give proof that the integral of the deviation of the film surface from its asymptotic equilibrium level vanishes. This general analytical result applies to arbitrary wall profiles. The region of validity of the surface rule is tested by numerical solutions of the Navier–Stokes equations.

Experimental and theoretical modelling of ice sheet–shelf grounding lines

11496
Tue·17:00·E

Grae Worster,† Herbert Huppert and Rosalyn Robison
University of Cambridge, UK†

We have used simple laboratory experiments with viscous fluids to explore the dynamics of grounding lines between Antarctic ice sheets and the freely floating ice shelves into which they develop. Ice sheets are shear-dominated gravity currents, while ice shelves are extensional gravity currents having zero shear to leading order. Though ice sheets have non-Newtonian rheology, fundamental aspects of their flow can be explored with Newtonian fluid mechanics. We have derived a mathematical model of this flow that incorporates a new dynamic boundary condition for the position of the grounding line, where the gravity current loses contact with the solid base. Good agreement between our theoretical predictions and experimental measurements gives confidence in the fundamental assumptions of our model, which can be incorporated into shallow-ice models to make important predictions regarding the dynamical stability of shelving ice sheets.

Structure of a pure-vapor–liquid contact line on a heated substrate: truncated adsorbed microfilms and the spreading coefficient

11955
Tue·17:20·E

Alexey Rednikov† and Pierre Colinet
Université Libre de Bruxelles, Belgium†

An inverse cubic law is adopted here for the disjoining pressure. A typical steady arrangement studied in the literature involves a liquid film approaching an adsorbed microfilm of constant thickness (AMFCT) at one end, while getting to a constant slope (the apparent contact angle) at the other. The microfilm, slightly hotter than the vapor, is in equilibrium with it. This is typically understood to be the perfect-wetting case. Here we rather study a family of steady solutions with the film starting out abruptly, as $(x - x_0)^{1/2}$, and, in the manner it was done by de Gennes for non-volatile liquids, associate the parameter of the family with the spreading coefficient. A positive (i.e. still within perfect wetting) critical value of the latter, below which our solutions are deemed to be preferred over the ones with AMFCT, is identified and depends on the applied temperature difference. Abruptly starting moving kinks of AMFCT are studied to clarify such a preference.

Are outside corners more difficult to coat than inside ones?

10910
Thu·09:15·1

Mathieu Sellier
University of Canterbury, New Zealand

Corners are well-known to induce defects in coated layers. These defects may have widespread, negative consequences. This paper explores the possibility to design corners capable of reducing them. The problem is formulated as a shape optimization problem for which one seeks the substrate profile which minimizes departures of the coated layer from an ideal uniform thickness. The coating thickness for a given substrate design is obtained by solving numerically the classical lubrication approximation. Results show that it is possible to significantly improve the coating uniformity at inside corners. Some improvement is also possible for outside ones but to a much lesser extent.

Sliding drops of generalized Newtonian liquid

10519
Thu·09:35·1

Leonard Schwartz,† Stephen O'Brien and Jean Charpin
University of Delaware, USA†

We model slow motion of a liquid drop having generalized Newtonian viscosity. The drop is sliding down a vertical wall. The model simulates three-dimensional unsteady motion using the long-wave or lubrication approximation. The static contact angle is finite. Wetting properties are built into the theory using disjoining pressure. For a Newtonian droplet on a vertical wall, all its properties can be collapsed into a single dimensionless control parameter and the viscosity enters only in the time scale. Generalized behavior uses the two-constant Ellis model. Thus different behaviors can be expected, depending on the parameter values. In order to define equivalence conditions so that the non-Newtonian character can be seen, we use the fall distance of the main droplet as the control variable. In general, shear thinning behavior retards drop break-up and the formation of a chain of isolated droplets.

Stability of a thin radially moving liquid sheet in the presence of acoustic excitation

11956
Thu·09:55·1

Mahesh Tirumkudulu,† Krishnaswami Ramamurthi and Aditya Mulmule
Indian Institute of Technology, Bombay, India†

Head-on impingement of two identical laminar liquid jets results in a thin circular liquid sheet whose thickness decreases as the inverse of the radius from the point of impingement. The sheet disintegrates into droplets at the sheet edge. We study the effect of sinusoidal acoustic disturbance on the break-up of the liquid sheet. Experiments were carried out for stable (smooth) as well as flapping regime of the sheet for $500 < We < 1300$, where We is the Weber number with respect to jet diameter. Detailed experiments show that at a fixed We and decibel level, the sheet responds to a set of specific frequencies lying within the range of 100-600 Hz with the frequency set varying with We. A linear stability analysis for constant thickness sheets suggests that while the growth rates for the thin sheets (< 100 microns) are frequency independent, the thicker sheets exhibit parametric resonance suggesting that it is the thicker part of the liquid sheet in the experiments that suffers excitation.

Hydrodynamics of reactive thin films

11312
Thu·10:15·1

Antonio Pereira,† Philip Trevelyan, Uwe Thiele and Serafim Kalliadasis
Imperial College London, UK†

We investigate the interaction between thin films and chemical reactions by using two prototype systems: a horizontal thin liquid film with a reactive mixture of insoluble surfactants on its free surface and a thin liquid film falling down a planar inclined substrate in the presence of an exothermic chemical reaction. In the first case the chemical reaction can destabilize the film and lead to the formation of free-surface solitary pulses. In the second case the chemical reaction has a stabilizing influence on the dynamics of the film and dampens the free-surface solitary pulses.

Flow structure in free surface film and Couette flow over non-planar substrates

11321
Thu·16:00·1

André Haas,† Harvey Thompson, Marc Wilson, Nuri Aksel, Markus Scholle and Philip Gaskell
University of Bayreuth, Germany†

Kinematically induced eddy formation in gravity driven free surface film and Couette flow over sinusoidally varying substrate with wavelength Λ is explored. The mean film thickness and the corresponding mean gap separation have the same size H in film and Couette flow, respectively. We show the significance of the two different Reynolds numbers $\mathrm{Re} = \mathrm{Re}_H$ and $\mathrm{Re} = \mathrm{Re}_\Lambda$ for eddy generation. We solve the governing equations in three ways, each exhibiting different degrees of complexity. These include: the Stokes flow limit employing an analytic lubrication analysis, a semi-analytic complex variable approach and the solution of the full Navier–Stokes problem via a finite element formulation. A sequence of new results is presented which reveal the impact of inertia and substrate geometry on eddy formation.

3D waves on liquid films and rivulets flowing down vertical plate

12145
Thu·16:20·1

Sergey Alekseenko,† Dmitriy Markovich, Sergey Kharlamov, Vladimir Guzanov and Aleksey Bobylev
Institute of Thermophysics, Russia†

The paper presents novel results on 3D wavy structures on rivulets and liquid films flowing down a vertical plate. Method of 3D LIF-visualization was used to register instant distribution of film thickness. Two scenarios of 3D waves evolution on liquid films were found to be universal. Stationary solitary waves are registered for liquids with sufficiently different physical properties. Wave amplitude and velocity are close to the theoretically predicted values. The family of wavy regimes on the free surface of rivulet is registered, including stationary step-like regimes, which are not observed for film flow. Existence of a narrow range of excitation frequencies was shown for which considerable increase of rivulet width occurs.

Rupture of a current-carrying fluid cylinder

11807
Thu·16:40·1

Jonathan Mestel,† Bill Ristenpart, Howard Stone and Tom Witelski
Imperial College London, UK†

When a standard fuse blows, a wire is melted by a large electric current. The fluid continues to conduct until rupture occurs. The magnetic pinching pressure behaves as I^2/R^2 where I is the current and R the cylinder radius, and so this may dominate surface tension as $R \to 0$. The late stages of break-up are analysed using a long-wave theory. If the current is taken to be constant then rupture is symmetric, but unstable. Realistically, the current should fall to zero at break-up. When inductance is taken into account, the theory predicts asymmetric rupture, which agrees well with numerical solution and experiment.

Resonance of surface waves in gravity-driven films over undulated bottoms

11314
Fri·09:15·6

Christian Heining,† Andreas Wierschem and Nuri Aksel
University of Bayreuth, Germany†

We study the gravity driven flow of a viscous liquid down an inclined wavy plane. Applying an integral boundary-layer approach we describe the film thickness and flow rate by two evolution equations. For steady flow the amplitude of the film thickness reaches a maximum at a certain Reynolds number. Investigating time dependent flow we obtain similar results in the presence of surface waves.

Centrifugally driven thin film flow over a fast rotating cone with arrays of micron sized holes

11812
Fri·09:35·6

Paul Duineveld† and Theo Stolk
Philips Consumer Lifestyle, Netherlands†

In a fruit juicer 2 phenomena play a role: a minimum rotational rate to have any juice output at all and a 100% yield is not possible. A centrifugally driven film flow over a fast rotating cone with arrays of micron sized holes is used as a model system. The juice flow is simplified by applying continuous flow of Newtonian liquid in the centre. With an extension of the theory of spin coating and the balance between centrifugal and capillary forces it can be shown that below a minimum rotational rate a spherical cap underneath the small holes prevents flow through them. At higher velocity the caps break-up and a simple calculation indicates that all liquid can easily pass the sieve. However from a balance between surface tension and centrifugal forces it is shown that the film is unstable and will de-wet between the holes. An expression for the waste flow is derived. The models are favourably compared with experiments and film break-up is observed with an image de-rotator system.

Unsteady contact melting

10515
Fri·09:55·6

Tim Myers,† Gift Muchatibaya and Sarah Mitchell
University of Cape Town, South Africa†

This paper deals with a model for contact melting. The problem is described by a coupled system of heat equations in the solid and melt layer, fluid flow in the melt, a Stefan condition at the melt interface and a force balance between the weight of the solid and the fluid pressure. Since the melt layer remains thin throughout the process, we use the lubrication approximation and assume that heat flow in the fluid is dominated by conduction across the film. In the solid we use the heat balance integral method. Results show that the film height has initial and final rapid increases, at intermediate times the height slowly increases. The quasi-steady state of previous models is never attained: this is shown to be an effect of neglecting the change of mass of the solid. The previously observed initial infinity velocity of the melt is shown to be due to neglecting the temperature variation in the solid or assuming perfect thermal contact.

FM12 :: Geophysical and environmental fluid dynamics

Chairs: William Young (USA) and Jiachun Li (China)

Mon	14:00–16:00	Room 5	Lectures
Tue	10:40–12:40	Room 6	Lectures
Tue	16:00–17:40	Room 6	Lectures
Thu	14:00–14:35	Room 6	Seminars
Fri	09:15–10:35	Room 1	Lectures

Equilibrium states of quasi-geostrophic vortices **10503** Mon·14:00·5

Takeshi Miyazaki,† Naoya Takahashi and Shintaro Hoshi
The University of Electro-Communications, Japan†

Geophysical flows are under the strong influence of the stable density stratification and the Coriolis force, which suppress vertical motion. At the lowest order, they are considered to be 2D. There have been many studies on 2D point vortex systems. The actual geophysical fluid motion is almost confined within horizontal planes, but different flow patterns are possible on different planes. The next order approximation is the 'quasi-geostrophic approximation', for which we investigate the statistical properties of vortices. Numerical simulations of a $N = 2000$ vortex system are performed using a fast special-purpose computer (MDGRAPE-3) for MD-simulations. The equilibrium distribution of the center region seems similar to that of the 2D point vortices. The 3D effects appears near the upper and lower lids through the tighter concentration of vortices around the axis of symmetry. The most probable distributions are determined based on maximum entropy theory.

Investigating the formation of wind-formed dune fields based on discrete dynamics **10784** Mon·14:20·5

Xiaojing Zheng† and Tianli Bo
Lanzhou University, China†

A 3D computer-simulation model for evolution process of dune field is proposed, where some of key factors, such as the physical mechanism of wind-blown sand movement, the intensity and direction of wind regime wind, acceleration in the windward side and the avalanche behavior in the lee slope are incorporated. The characteristics and behavior, such as the 'absorption' and 'ejection', of simulated dune field have a satisfactory agreement with the existing field observations, the results correspond well with the real dune field on time and space scale. The effect of the intensity of wind regime and the diameter of sand particle on the migration of the dune is first revealed. It is found that there exists a sand thickness threshold which determines whether the dune field evolves into barchan or transverse pattern. Diversity of dune field system is substantial discussed emphasizing on influence of wind direction.

The effect of thermal diffusion on the stability of strongly tilted mantle plume tails **10891** Mon·14:40·5

Ross Kerr† and Catherine Meriaux
The Australian National University, Australia†

The effect of thermal diffusion on the gravitational stability of strongly tilted mantle plume tails is explored by investigating the behaviour of a rising horizontal cylindrical region of buoyant viscous fluid. At low Reynolds numbers and large viscosity ratios, the convective flow depends on only one dimensionless parameter: the Péclet number. From a theoretical analysis, we find that the rising cylindrical region is stable at small Péclet numbers and unstable at large Péclet numbers. These predictions are confirmed by a series of laboratory experiments which show that the transition from stable rise to gravitational instability occurs at a critical Péclet number of about 140. When our results are applied to the Earth, we predict that thermal diffusion will stabilize plume tails in both the upper and lower mantle.

Experimental study on propagation velocities of water surface ripples and turbulence in an open-channel flow

10963
Mon·15:00·5

Hitoshi Miyamoto
Kobe University, Japan

Propagation velocities of both water surface ripples and turbulence in an open-channel flow were experimentally investigated. We used a simultaneous image measurement method to obtain instantaneous velocity vectors and the corresponding water surface profiles in a vertical cross section of the open-channel. The space-time correlation analysis of the water surface fluctuations and turbulence disclosed that the propagation velocity of the water surface ripples was always smaller than the mean bulk velocity, while that of the turbulence above the near bed region was the same as the mean velocity, which is well-known as Taylor's hypothesis of the frozen-turbulence approximation. It was found out that the ratio of the propagation velocity of the water surface ripples to the mean bulk velocity became smaller as the Froude number decreased.

Effects of upstream disturbances in a model of headland wakes

11134
Mon·15:20·5

Melanie O'Byrne,† Ross Griffiths and Graham Hughes
The Australian National University, Australia†

We quantify the effects of upstream topography on the wake of an idealised headland (a sidewall protrustion) using ultrasonic Doppler velocity measurements. Over a range of Reynolds numbers, perturbing the incident flow results in a wake that both contains weaker eddies overall and decays more rapidly with distance downstream of the headland, yet the wake recirculation may be up to 25 per cent longer than in the absence of upstream topography. Disturbances incident on the headland modify the stability of the shear at the edge of the wake and partially suppress the formation of coherent eddy structures in its lee. The kinetic energy in the region of the wake close to the headland is distributed over a greater spanwise extent and a broader range of (eddy) frequencies, resulting in a surprisingly rapid dissipation of eddies with distance downstream.

Mixing in baroclinic exchange flows and its dependence on topography

11174
Mon·15:40·5

Ross Griffiths,† Graham Hughes, Andrew Hogg and Tjipto Prastowo
Australian National University, Australia†

The overall amount of mixing achieved in hydraulically controlled, buoyancy-forced two-layer exchange between two reservoirs is measured for a set of strait and sill geometries. The total amount of mixing is directly measured, converted to potential energy terms and reported as a bulk mixing efficiency. For simple lateral constrictions the efficiency asymptotes at large Reynolds numbers to a constant value of 11%, independent of constriction width and length. For a vertical weir within the constriction the result is unchanged, whereas for a sill with sloping sides the efficiency is reduced to 8%. These cumulative efficiencies are smaller than the maximum mixing efficiency of 20% commonly assumed in ocean modelling and imply that a greater rate of energy supply will be required to achieve a given rate of mixing.

The viscous phase of horizontal gravity currents: how is the time evolution of the front selected?

11081
Tue·10:40·6

Yannick Hallez† and Jacques Magnaudet
Institut de Mécanique des Fluides de Toulous, France†

We investigate numerically the viscous phase of a gravity current generated by a lock-exchange on a rigid surface. We run both 2D and 3D cylindrical simulations to compare numerical results for the front position $x_f(t)$ with the 2D theoretical prediction of Huppert (1982) ($x_f(t) \sim t^{1/5}$) and the 2D and 3D predictions of Seon et al. (2007) ($x_f(t) \sim t^{1/2}$). We show that the proper exponent is selected by the flow Reynolds number and the initial volume of the released fluid. More precisely, our simulations reveal that the physical mechanism responsible for the selection of the exponent is the presence or absence of a wave generated by the reflection of one of the fronts on the endwall of the channel. When such a wave does not exist (i.e. the initial configuration is symmetric), our numerical predictions, both for the front position and the shape of the current, are in excellent agreement with the recent theory of Seon et al. (2007).

Inertia-gravity wave generation: a geometric-optics approach

11337
Tue·11:00·6

Jacques Vanneste† and Jonathan Aspden
University of Edinburgh, UK†

The slow motion that dominates the large-scale dynamics of the atmosphere and oceans can generate relatively fast inertia-gravity waves through spontaneous-generation and instability mechanisms. Capturing these mechanisms, either numerically or analytically, present a number of challenges because the waves typically have small amplitudes and small spatial scales. Previous asymptotic work has demonstrated the existence of these mechanisms, showing that they are exponentially weak in the limit of small Rossby number. Here we consider a different asymptotic approach which relies on the spatial-scale separation between the waves and the slow flow but makes no assumption on the Rossby number. The approach proposed differs from standard WKB theory for waves because the waves are considered in the so-called wave-capture regime, where their intrinsic frequency can be neglected compared to the Doppler shift.

Forward energy cascade of geostrophic turbulence via near-boundary instabilities

11631
Tue·11:20·6

William Dewar† and Andrew Hogg
Florida State University, USA†

Dissipation of energy from mesoscale, or “balanced” flow is an important unresolved problem in oceanography. We propose that topography is central to the loss of energy from balanced to unbalanced flows. In support of this conjecture, we herein describe high resolution numerical calculations and analytical considerations. The arguments point to the central role played by the no-normal flow boundary condition imposed by the topography; in response balanced flows develop finite amplitude unbalanced components. The conditions under which this occurs appear to be very broad, reflecting the simplicity of the effect. It is proposed that this mechanism should be active near topography in the ocean, providing a sink of energy for mesoscale vortices and a source of energy for ocean mixing.

Transcritical small disturbance theory for flow over topography **11513** Tue·11:40·6

Ted Johnson,† Gavin Esler and Owen Rump
University College London, UK†

Cloud patterns show "shock or bow" waves forced by mountains penetrating cloud layers. These are reproduced in experimental observations of finite amplitude interfacial waves forced by a surface-mounted obstacle towed through a two-layer fluid when the fluid is otherwise at rest and when it is otherwise rotating as a solid body. Transcritical flow, where the Froude number F of the oncoming flow is close to unity and the obstacle height M relative to the layer depth is small, is shown to be precisely analogous to transonic flow over a thin aerofoil. The drag exerted by the obstacle on the flow takes the form $D(\Gamma)M^{5/3}$, where $\Gamma = (F-1)M^{-2/3}$ is a transcritical similarity parameter, and D is a function which depends on the shape of the "equivalent aerofoil" specific to the obstacle. The theory is verified numerically by comparing results from a shock-capturing shallow water model with corresponding solutions of the transonic small disturbance equation.

Solution of some vortical free boundary problems arising in ocean flows **10090** Tue·12:00·6

Nicholas McDonald† and Ted Johnson
University College London, UK†

The flow of a two-dimensional current with uniform vorticity along a boundary defines a free boundary problem in which Poisson's equation determines the shape of the fluid layer, or current, in contact with the boundary. Using potential plane mapping techniques, explicit solutions are found for steady vortical flows driven by sources located in a plane wall and for gap-leaping flows. In each case the unsteady evolution of flows toward these steady states is studied using a version of contour dynamics, appropriately modified to take into account the presence of boundaries. For cases in which steady solutions do not exist, the numerical solutions reveal persistent eddy-shedding events.

The behaviour of dilute particle suspensions in waning flows **11114** Tue·12:20·6

Robert Dorrell† and Andrew Hogg
Bristol University, UK†

Dilute suspensions of particles in a turbulent flow are modeled using an advective-diffusion equation derived from the principle of mass conservation, where the correlation between fluctuations are modeled as a diffusion process. The resulting equation is solved subject to flux boundary conditions in terms of the Rouse number, which measures settling velocity relative to a turbulent velocity scale. Solutions have been found to describe the behaviour of the particle concentration profile during a change in flow conditions. For small Rouse numbers, dimensionless particle response time is independent of particle size, however at large Rouse numbers particle response time is inversely proportional to particle size squared. Further, both of these results are independent of the spatial structure of the turbulent diffusion model used. It is argued that the results explain traits of particle sedimentation observed in experimental waning flows, including grading and growth rate of the deposit.

The large-scale effect of mesoscale ocean–atmosphere coupling

11706
Tue·16:00·6

Andrew Hogg,† William Dewar, Pavel Berloff and Sergey Kravtsov
The Australian National University, Australia†

Small-scale variation in wind stress due to mesoscale coupling are included in an idealised model of the double gyre ocean circulation. Mesoscale coupling alters the temporal and spatial scale of Ekman pumping driving the two gyres, and has an unexpectedly large effect on the mean circulation. The effect on the mean flow depends upon the variability of the forcing (rather than its mean) and is significant because forcing variance is naturally concentrated in dynamically sensitive regions. An important dynamical component of this effect is due to destabilisation of the flow, leading to enhanced eddy fluxes between the gyres. We suggest that mesoscale coupling modifies the first order response of the ocean to wind stress forcing.

Adjustment processes in horizontal convection

11684
Tue·16:20·6

Graham Hughes† and Ross Griffiths
The Australian National University, Australia†

'Horizontal convection' is the overturning circulation established in a fluid when differential heating is maintained along one horizontal boundary. We examine how thermally-equilibrated convection responds if the differential heating is suddenly perturbed. When the perturbation temporarily supplies destabilizing buoyancy to the flow, an initially more vigorous, but otherwise similar, convective state results. Conversely, when the perturbation is of the opposite sign, the convection is dramatically and rapidly shut down. In both cases, the convection eventually re-equilibrates to a state close to the initial circulation. The flow evolution and the re-equilibration timescales are relevant to understanding how the global overturning circulation in the oceans may respond to changes in surface buoyancy forcing, such as those due to global warming.

Three-dimensionality in electromagnetically driven shallow flows

10737
Tue·16:40·6

GertJan van Heijst,† Rinie Akkermans, Leon Kamp and Herman Clercx
Eindhoven University of Technology, Netherlands†

The canonical laboratory set-up to study two-dimensional turbulence is the electromagnetically driven shallow one- or two-fluid layer. Stereo-Particle-Image Velocimetry measurements in such driven shallow flows revealed strong deviations from quasi-two-dimensionality, which are attributed to the inhomogeneity of the magnetic field and, in contrast to what has been believed so far, the impermeability condition at the bottom and top boundaries. These conjectures have been confirmed by numerical simulations of shallow flows without surface deformation, both in one- and two-fluid layers. The flow simulations reveal that the observed three-dimensional structures are in fact intrinsic to flows in shallow fluids because they do not result primarily from shear at a no-slip boundary: they are a direct consequence of the vertical confinement of the flow.

Physics of the mesoscale atmospheric turbulence: laboratory experiments

11530
Tue·17:00·6

Michael Shats,† Hua Xia, Horst Punzmann and Gregory Falkovich
The Australian National University, Australia†

To identify the energy sources powering atmospheric turbulent winds, it is crucial to understand the energy distribution over, and the energy transfer between, different scales. New experimental results in two-dimensional turbulence shed light on the origin of the Nastrom–Gage spectrum of

kinetic energy and of the energy flux in the mesoscale atmospheric turbulence. It is shown that the large-scale flows strongly modify statistical properties of turbulence leading to apparent deviations from the Kolmogorov–Kraichnan theory. The isotropic turbulence result, including the inverse energy cascade, is revealed by the mean flow subtraction, a technique which should also be useful in the analysis of atmospheric data.

Absence of small-scale fluctuations of high-Prandtl number scalars in stratified turbulence

10223
Tue·17:20·6

Hideshi Hanazaki,[†] Kazuhiro Konishi and Takehiro Miyao
Kyoto University, Japan[†]

It has often been assumed that fluctuations of scalars with small molecular diffusivities (Prandtl number $Pr > 1$) can survive at length scales smaller than the Kolmogorov scale, as predicted by Batchelor (1956). This would be true to passive scalars, but we demonstrate here that it would not be applied to buoyant/active scalars such as heat and salt, whose distribution affects the fluid motion. Results of direct numerical simulations for a double-diffusive system, i.e. a system with two active scalars which constitute density stratification, show that the fluctuations of active scalars with high Pr disappear at the Kolmogorov scale. This implies that the fluctuations of heat ($Pr = 6$) and salt ($Pr = 600$) in the ocean might disappear at much larger scales than have been expected. This vanishing of small-scale scalar fluctuations has been observed similarly in single-diffusive stratified turbulence, since its origin would be in the exchange between kinetic energy and potential energy.

Some investigations into near surface wind and saltation intensity in mining area

10261
Thu·14:00·6

Ning Huang,[†] Xiaojing Zheng and Feng Shi
Lanzhou University, China[†]

The field observations on blown sands and sand storm are usually limited to wind velocity and dust concentration 10 meters above surface. Based on a self developed system, which can simultaneously measure wind profile, sand transport intensity and sand flux in real time, we measured physical quantities such as pulsed wind velocity at near surface, sand transport intensity, sand flux, temperature and humidity with 1Hz frequency on sand dunes in Minqing area, which locates between edges of the Badain Jaran Desert and the Tengger Desert. The analysis on the measured data shows that wind fluctuates with high frequency and sand saltation is with high level of intermittency accordingly. Time step affects the correlation between wind velocity and saltation intensity and it can attain as high as 0.8 when the time step is higher than 30 second, which means that moving sands can fully respond to the fluctuation of wind whose frequency is under 30 second.

PIV measurements in the immediate wake of a cactus-shaped cylinder

11853
Thu·14:05·6

Ghanem Oweis
American University of Beirut, Lebanon

Cactus trees, such as the saguaro cactus, have an interesting aerodynamic shape. Basically, their geometry consists of a long cylindrical body, with surface grooves aligned parallel to the cylinder axis. It is believed that these grooves might have resulted from an evolutionary process aiming, at least partially, to minimize the aerodynamic loading on the tree. We report on PIV and wind tunnel studies of the flow in the immediate wake of a symmetric, cactus-shaped cylinder with 8 grooves. The flow behind a similarly sized smooth circular cylinder (73 mm dia.) is also measured. Multiple flow speeds up to 45 m/s are investigated. The mean flow characteristics in the cactus wake flow are compared to the benchmark circular cylinder case.

Experiment and simulation of unsteady sand mass flux in the near-surface layer

11055
Thu·14:10·6

Ping Wang,† Xiaojing Zheng, Jinghong Zhang and Wenwen Hu
LanZhou University, China†

In order to describe effects of gust on the sand transport rate in short timescale and predict the actual transport rate, fast response instrumentations were used to measured continuously and synchronously the wind velocity and sand transport strength respectively in bare and sandy interdunes at the edge of Badain Jaran desert in China. Analysis of the experimental data using the discrete wavelet transform method shows random characteristic of boundary turbulence. A general prediction model is proposed which proved efficient in reflecting the intermittency of natural wind and is used to simulate the sand transport strength and the transport rate basing on the grain size distribution of the sand sample taken near the experimental spot. Results show that sand transport rate in unsteady gust is larger than that in steady logarithmic wind and suggest that previous theoretical prediction neglecting gust may underestimate the factual sand transport rate in natural wind.

Hydraulic modeling of runoff yield in small watersheds

11142
Thu·14:15·6

Qingquan Liu† and Yi An
Chinese Academy of Sciences, China†

The runoff caused by rainfall is the most important of the factors which affect soil erosion process of a watershed. A hydrodynamic distributed model of watershed runoff yield, comprising three components is presented in this paper. The first component uses the modified Green & Ampt equation to predict the process of soil infiltration. The second component applies the 2D kinematic wave model for the spatial and temporal prediction of flow depth on an elementary slope. The final component determines flow directions and the process of flow concentration. A new method is presented for describing the process of runoff concentration in a small watershed. This model can simulate space-time processes of runoff formation for the small basins. The numerical models were tested by comparison of simulation resulted with observed data. It was found that flood discharges output from the simulation are compared well with measured data.

Thermodynamics of irreversible transitions in the oceanic general circulation

11357
Thu·14:20·6

Shinya Shimokawa† and Hisashi Ozawa
National Research Institute for Earth Science and Disaster Prevention, Japan†

In this study, we investigate a transition process among multiple steady states of oceanic circulation under the same set of boundary conditions, and clarify the relationship between entropy production and the strength and direction of fresh water perturbations. Our results are found to be consistent with “the principle of maximum entropy production (MEP)” in non-equilibrium thermodynamics, and can be understood in a consistent manner by a concept of “dynamic potential” that regards the rate of entropy production as a kind of thermodynamic potential. MEP could be a general thermodynamic principle that determines the behavior of oceanic circulation in response to external perturbations, leading to a better understanding of abrupt climate changes in paleoclimate and global warming.

A simple model to predict the seabed profile under pipelines **12048** Thu·14:25·6

Lei Li† and Mian Lin
Institute of Mechanics, CAS, China†

In order to guarantee submarine pipeline security, the profile of seabed and the gap ratio should be known first for they influence the hydrodynamics force on the pipeline. For engineer, to search an efficient method to predict the profile under the pipeline is necessary. A mechanical model for local scour under pipelines is presented by three aspects: potential theory, wake correction and sediments transportation. With the model, the flow fields and the process of local scour around pipeline near the seabed are simulated. And finally the results show that the model can simulate the upstream profile and obtain the maximum scour depth effectively.

New approach to mathematical modeling of admixture transport in free-surfaced streams **10970** Thu·14:30·6

Konstantin Nadolin
Southern Federal University, Russia

Spreading of the passive nonconservative admixture in the natural low-curved open stream is considered. The channel bed is assumed to be known and quite smooth and the stream is assumed to be lengthy and shallow, so the ratio of the channel's characteristic width to its characteristic length and channel's characteristic depth to its characteristic width are small parameters. A set of mathematical models are derived by the small parameter technique, starting from the 3D Reynolds equations for the incompressible fluid (coupled with Boussinesq turbulence hypothesis) and the diffusion equation for the moving medium. The particular feature of these reduced models is taking into account the stream cross-structure that allows us to study the contaminant spreading in a channel with varying width and depth more accurate than with depth-averaged models (for example, to catch the phenomenon of rising the near-surface opposite flow which may be caused e.g. by the wind action).

Evidence of anisotropy of small scale turbulence in the laboratory model of an atmospheric cloud **11315** Fri·09:15·1

Piotr Korczyk,† Szymon Malinowski and Tomasz Kowalewski
Instytut Podstawowych Problemów Techniki, Polska Akademia Nauk, Poland†

Cloudy air, containing small water droplets, undergoes mixing with the unsaturated environment inside the cloud chamber in the process resembling smallest scales of entrainment and mixing in real clouds. Particle Image Velocimetry (PIV) applied to images from the chamber interior is used to investigate dynamics of the process in scales from 0.07 mm to few centimeters, i.e. an order of magnitude better than the Kolmogorov length scale. Results of laboratory experiments clearly indicate that evaporative cooling of cloud water at the cloud-clear air interface affects in small-scale turbulence statistics. This can affect droplets collision rate being responsible for drizzle formation.

Particulate gravity currents along v-shaped valleys

11091
Fri·09:35·1

Joe Monaghan,[†] John Mansour, Herbert Huppert and Catherine Meriaux
Monash University, Australia[†]

This paper reports on studies of particulate gravity currents at high Reynolds number flowing along a tank with a V-shaped valley. We use both experiments and a box model to determine the primary features of the flow The resulting motion and deposit pattern differ significantly from those for the propagation of a particulate gravity current along a tank with flat bottom. In particular, the mass deposited per unit area across the V-shaped valley, for any position along the valley, is much larger in the central part of the valley than it is on the flanks. We find that the results can be described with remarkable accuracy by a box model using a generalization of the equation for sedimentation from a turbulent medium.

On numerical simulation of tropical atmospheric intraseasonal oscillation (MJO)

12157
Fri·09:55·1

Jian Ling,[†] Chongyin Li and Jia Xiaolong
Institute of Atmospheric Physics, China[†]

Using Long-term integrations in the SAMIL CAM2, we study the impacts of convection parameterization scheme (particularly the heating profile), model resolution and momentum mixing by cumulus convection on the MJO simulation. The simulated MJO in two GCMs with different cumulus parameterization schemes are so different. The simulations and experiments indicated further that when the largest heating is in the mid-lower troposphere, the simulated MJO is more realistic than the others. The three different resolutions in SAMIL all produced the basic features of the MJO, these are no essential differences among these model results. It is indicated that resolution is not essential for simulating the MJO in the GCM. The momentum transport (mixing) by cumulus convection is an important process in tropical atmosphere, but the numerical experiment shows that the introducing of momentum transport in the GCM is unfavourable to simulate the realistic MJO.

Separating flow over two-dimensional rough hills

11617
Fri·10:15·1

Juliana Loureiro,[†] Andre Monteiro, Fernando Pinho and Atila Silva-Freire
Federal University of Rio de Janeiro, Brazil[†]

Two new data sets for turbulent flow over a steep, rough hill are presented and compared with previous experimental results for flow over a steep, smooth hill. The experiments are conducted in a water channel for two different Reynolds numbers. As it turns out, for the lower Reynolds number, the extent of separated flow is much reduced by the roughness as compared to the smooth wall case. For the second set of experiments, Reynolds number is increased about ten times. The region of separated flow is then observed to increase, but to a still shorter length than that recorded for the smooth surface. In all, twenty three measuring stations are analyzed through laser Doppler anemometry. Mean velocity as well as turbulent quantities are measured. To find the wall shear stress, global optimization algorithms based on a specialized law of the wall formulation are used.

FM13 :: Low-Reynolds-number flow

Chairs: Osamu Sano (Japan) and Elisabeth Guazzelli (France)

Tue	14:55–15:10	Hall A	Seminars
Wed	10:40–13:00	Hall C	Lectures
Thu	09:15–10:35	Room 6	Lectures
Thu	16:00–17:00	Room 2	Lectures

On the effects of atmospheric pressure, air concentration in a fluid, and the surface roughness on a solid-sphere motion along a wall

10919
Tue·14:55·A

Alexander Prokunin
Moscow State University, Russia

We study experimentally the influence of the atmospheric pressure and the dissolved air upon a slow motion of a heavy ball along a wall in the incompressible fluid. This influence is caused by generation of a cavitational air microbubble in the lubrication layer between the ball and wall, which makes possible contactless/contact motion of the ball along the wall. We find a parameter which specifies the stationary motion of the ball along the wall with the generation of an air bubble (gaseous cavitation), including a limiting case of degasified fluid (vapor cavitation). This parameter is proportional to the difference between the atmospheric pressure and the one corresponding to the equilibrium concentration of the air dissolved in fluid. If the parameter is negative, a non-stationary motion of the ball is possible. In the case of contact we study the effect of the ball surface roughness upon the ball motion. A phenomenological theory of the ball motion is formulated.

A fast boundary element method for Stokes flow

11688
Tue·15:00·A

Kian-Meng Lim,† Xuefei He and Siak-Piang Lim
National University of Singapore, Singapore†

In this paper, we present a fast algorithm to solve Stokes flow problems using the boundary element method (BEM). This fast algorithm is based on the fast Fourier transform on multipoles (FFTM) method that has been developed for the Laplace equation. The FFTM method uses multipole moments and their kernel functions, together with the fast Fourier transform (FFT), to accelerate the far field computation. The algorithm is applied to calculate the average drag force on numerous spheres in a tube. The FFTM algorithm is shown to provide an efficient computation for large problems with more than 100 spheres and 30,000 elements.

Arbitrary oscillatory Stokes flow past a porous sphere: Faxen's laws

10793
Tue·15:05·A

Raja Sekhar,† Mirela Kohr and Jai Prakash
Indian Institute of Technology, Kharagpur, India†

Faxen derived expressions for the drag and torque exerted by an exterior steady Stokes flow on a rigid sphere, and Pozrikidis presented similar results for unsteady Stokes flow, by using the singularity method. In case of Stokes flow past a porous sphere using Darcy equation inside the porous sphere Saffman's condition is used in general. But, the validity of Saffman's condition that is derived under steady flow conditions, to oscillatory flows is not known until Looker *et al.* have shown that it still can be applied to such flows if the frequency of oscillation is not too high.The main aim of this paper is to derive Faxen's laws in the case of arbitrary oscillatory Stokes flow past a porous sphere and to establish the corresponding results in the limiting case of oscillatory Stokes flow past a rigid sphere, or in the case of translational oscillations of a porous sphere.

Eddy reversals in three dimensions

11228
Wed·10:40·C

Christopher Hills
Dublin Institute of Technology, Ireland

The phenomenon of eddies in low Reynolds number flows has been observed for many geometries. Occurring most frequently in corner geometries, it has also been shown that eddies occur for the slow flow within a cylindrical annulus. This geometry is of particular current interest with the emphasis on developing micromixers, micromachinery and lab-on-a-chip technology. If the driving mechanism responsible for the eddies is reversed then it is anticipated that the eddies themselves should reverse. The mechanism of eddy reversals has been demonstrated for the classical case of eddies in two-dimensional corners showing that eddies can be annihilated through this mechanism. We will present a preliminary study of the generation of eddies within the cylindrical annulus through two important practical mechanisms (magnetohydrodynamic forcing and rotation of a boundary) and initiate for the first time an investigation of reversals in a three-dimensional geometry due to oscillatory driving.

Viscous flow past two spherical cavities in porous media: application to drug delivery system

10523
Wed·11:00·C

Osamu Sano
Tokyo University of Agriculture and Technology, Japan

We have calculated the effect of macroscopic 2D cavities in an otherwise homogeneous porous media. When the cavity size is large compared with the interstices of the constituent materials, the volume flux Q_c and the velocity at the center of the cavities U_0 were predicted to be greatly enhanced, which were confirmed experimentally. The analysis has been extended to a spherical cavity, which revealed the increase of Q_c and U_0 as large as three times and six times, respectively, without it. In this paper we extend the results so as to include the interaction of two spherical cavities. The dependences of the center-to-center distance and the orientation of the cavities with respect to uniform flow on the Q_c and U_0 are discussed.

Three flow regimes of a viscous jet falling onto a moving surface

10713
Wed·11:20·C

Andriy Hlod,† Mark Peletier, Fons van de Ven and Annemarie Aarts
Eindhoven University of Technology, Netherlands†

During the fall of a viscous jet under gravity from an oriented nozzle onto a moving surface, three flow regimes are distinguished. A flow regime is characterized by a convexity of the jet shape, and depends on the flow velocity at the nozzle, the belt velocity, the falling height, and the fluid properties. For a viscous fluid falling from a small height with large belt velocity the jet shape is convex and touches the belt tangentially. In the second regime the jet is vertical and this occurs with small flow velocity at the nozzle and large falling height. The third regime occurs for large flow at the nozzle, and the jet shape is concave (aligned with the nozzle orientation), similar to a ballistic trajectory. The jet is modeled using a thin-jet approximation and including viscous tension, gravity, and inertia. The parameter regions for the three flow regimes are found. The model equations are solved and the results agree with the experimental observations.

The irreversible effect of cavitation in near-contact region

10652
Wed·11:40·C

Alan Graham,† Shihai Feng, Patrick Reardon, Cynthia Heath and Marc Ingber
Institute for Multiscale Materials Studies, USA†

The hydrodynamic behavior observed for a sphere released under gravity in a Newtonian liquid is not consistent with that predicted by classical continuum theory when the sphere is near a solid wall. An irreversibility arises in the velocity of the sphere as it approaches and recedes from the plane that cannot be accounted for using continuum hydrodynamic equations alone. Earlier experiments on spheres falling from a plane were conducted under conditions such that this irreversibility could be attributed to the surface roughness of the spheres. In this investigation, we extend these studies to situations where the pressure field between the receding sphere and the plane drops to the vapor pressure of the fluid and cavitation occurs. Experimental data supports the theoretical prediction for a sphere's motion based on the irreversible effect of cavitation.

Flow of microcapsules in small pores: a method for determining the elastic properties of the membrane

11309
Wed·12:00·C

Dominique Barthès-Biesel,† Johann Walter, Yannick Lefebvre, Eric Leclerc and Florence Levy
Université de Compiègne, France†

The objective of this work is to find a method to measure the mechanical properties of the membrane of artificial microcapsules. The technique consists of flowing initially spherical microcapsules into a cylindrical microchannel of comparable dimensions and measuring the particle deformation and velocity as a function of flow rate and relative size ratio between the capsule and pore diameters. Assuming a specific constitutive law for the capsule wall material, the membrane shear elastic modulus is determined by means of an inverse method based on a numerical model of the mechanics of a flowing capsule. The method is illustrated on microcapsules with an average diameter of 50 μm, enclosed by a polymerised ovalbumin membrane. When a neo-Hookean constitutive law is assumed for the interface, the method yields a constant value for the membrane shear elastic modulus independently of capsule size or deformation.

Weak inertial effects associated with oscillating pressure in a 3D channel

11490
Wed·12:20·C

Guibert Romain,† Alain Bergeon and Franck Plouraboué
University of Toulouse, France†

We analyze the inertial effects in confined pulsating flows in three dimensions for which the length-scale associated with the transverse direction is much smaller than the longitudinal scale, the ratio of which is a small parameter ϵ. We solve analytically for the transverse dependence of the 3D-velocity field including Stokes layers, and numerically for the its longitudinal dependence. The flow characteristics are studied versus the Womersley number for some family of 3D cavity. Breaking the channel symmetries leads to non-zero steady streaming flux with quadratic pressure drop dependence.

Stokeslet induced flows in the vicinity of a hybrid compound droplet

11949
Wed·12:40·C

Devanayagam Palaniappan
Texas A&M University, USA

Analytic solutions for a hybrid compound droplet submerged in a stokeslet (point force) flow are obtained in singularity forms. The geometry is modeled as two overlapping spheres (a vapor and a liquid sphere) intersecting at right angles and the flow is assumed to be axisymmetric. The exact solutions for the streamfunctions are obtained by successive application of reflection principle. The image system is found to consists of stokeslets and higher order Stokes multipoles all located inside the compound droplet. The streamline plots in the case of a pair of opposite stokeslets display nice flow patterns. Toroidal eddies are discovered for a variety of parameters associated with the problem. The eddy structures appear to change significantly as the parameters are varied over a wide spectrum of values. The present results may be of some interest in ciliary propulsion of microorganisms and may also be used to test/validate numerical codes involving multiphase droplets.

Periodic orbits of Stokesian dynamics

11682
Thu·09:15·6

Maria Ekiel-Jezewska
Instytut Podstawowych Problemów Techniki, Polska Akademia Nauk, Poland

A family of periodic in time solutions of the Stokesian dynamics has been found numerically for three identical spherical particles settling under gravity in a vertical plane. The particles stay close to each other and hydrodynamic interaction between their surfaces is essential to detect the oscillations, which have not been found in the point-particle simulations. The periodic orbits are responsible for 'chaotic scattering' of the particles, which come and stay for some time sufficiently close to these orbits before 'escaping'. The existence of such periodic solutions is of fundamental importance for understanding evolution of many-particle systems, and also as a benchmark for testing numerical procedures used to evaluate the Stokesian dynamics.

Large-scale simulations of emulsion flow through a granular material

11884
Thu·09:35·6

Alexander Zinchenko[†] and Robert Davis
University of Colorado at Boulder, USA[†]

A method is developed, capable of direct multidrop-multiparticle simulations of emulsion flow through a granular material at low Reynolds numbers. The solid granular particles form a random densely-packed arrangement rigidly held in a periodic box under the action of normal and frictional contact forces. Deformable emulsion drops, comparable in size with the particles, squeeze under a specified average pressure gradient. The solution is based on boundary-integral equations with novel desingularizations. We study the flow rate-pressure gradient relationships for both the continuous and drop phases, their dependence on the size ratio, viscosity ratio and the capillary number, and critical conditions when the drops are blocked in the pores by capillary forces. A challenge, especially for near-critical squeezing, is that high resolutions (at least, ~ 10000 boundary elements per surface) and many time steps (~ 10000) are required; the use of multipole acceleration is crucial .

Low-Reynolds streaming in a cavity: an illustration of inviscid flow **10170** Thu·09:55·6

Josue Sznitman† and Thomas Roesgen
University of Pennsylvania, USA†

Low-Reynolds number flows are typically described by the equations of creeping motion, where viscous forces are dominant. We illustrate using Particle Image Velocimetry (PIV) an example of small-scale boundary driven cavity flows, where forcing relies on viscous mechanisms at the boundary but resulting steady flow patterns are, however, inviscid. Namely, we have investigated acoustic streaming flows inside an elastic spherical cavity. Here, the inviscid equations of fluid motion are not used as an approximation, but rather come as a result from the general solution of the creeping motion equations solved in the region interior to a sphere.

Expanding volumes of channelized viscous gravity currents **10874** Thu·10:15·6

Daisuke Takagi† and Herbert Huppert
University of Cambridge, UK†

Channelized flows of viscous gravity currents are treated theoretically and experimentally. A Newtonian viscous fluid is supplied from a point source at a rate such that the fluid volume grows with time t like t^α for some prescribed constant α. The topography consists of either a flat or an inclined semi-infinite channel with a height that increases in the cross-stream direction y like y^n for some constant n. The resultant current evolves with a self-similar structure and extends along the flow with time like t^c, where c depends on the topography and the evolution of the fluid injection rate. We analyze this dependence in detail and determine that when the viscous fluid is injected at a rate with $\alpha < 1/2$ along a horizontal boundary or $\alpha < 1$ down a slope, $n = 1$, corresponding to a wedge-shaped channel, is optimal for transporting the fluid quickly.

Periodic fundamental solution of the two-dimensional Stokes flow **10380** Thu·16:00·2

Hidenori Hasimoto
The University of Tokyo, Japan

Doubly periodic fundamental solutions of the Stokes flows parallel and perpendicular to the general doubly periodic lattice of cylinders are constructed in terms of the Weierstrass elliptic functions. The relation to the solutions in Fourier serie as well as the general Darcy law is discussed.

Dynamics of the snail ball **10520** Thu·16:20·2

William Young,† Neil Balmforth, John Bush and David Vener
Scripps Institution of Oceanography, USA†

I will consider the dynamics of a magic trick, the snail ball, which is marketed with the explanation: “A small metallic gold ball just over 2 cm in diameter ... the ball does roll, but does so incredibly slowly. To an audience it seems baffling... inside the ball, which is actually hollow, there is a viscous liquid and a smaller ball which is heavy...it is the smaller heavier ball which determines the pace and this is slow because of the viscous liquid”. I will consider an experimental cylindrical analog consisting of a hollow cylindrical shell, a nested solid cylinder, and a gap filled with viscous fluid. A mathematical model is compared with simple experiments and the disagreement between theory and experiment indicates that the size of contact asperities plays a crucial role in determining the average rolling speed. This hypothesis is supported by coating the inner cylinder with sandpaper of different grades, which changes the rolling speed.

Low Reynolds number swimming beneath a free surface

11123
Thu·16:40·2

Darren Crowdy,† Anette Hosoi, Eric Lauga, Sungyon Lee and Ophir Samson
Imperial College London, UK†

Motivated by the motion of water snails that move by deforming their bodies beneath a free capillary surface, we study simple analytical models to gain insight into the mechanism of locomotion. Such swimmers use their interaction with the free surface to "break the symmetry" and overcome the obstruction to displacement presented by the well-known "scallop theorem". By combining singularity theory (to describe the swimmer) with conformal mapping (to describe the free surface), a class of exact solutions to a model system is derived and systematically studied to produce an optimal swimming protocol.

FM14 :: Magnetohydrodynamics

Chairs: Sergey Surzhikov (Russia), Jean-François Pinton (France) and Rainer Hollerbach (UK)

Tue	14:45–14:55	Room 4	Seminars
Thu	09:15–10:35	Room 8	Lectures
Thu	16:00–17:00	Room 3	Lectures

Influence of magnetic and electrical fields on a thin layer of electrically conducting liquid

10391
Tue·14:45·4

Hamid Abderrahmane[†] and Georgios Vatistas
Concordia University, Canada[†]

The paper deals with the stationary waves traveling at the free surface of thin layer of an electrically conducting fluid flowing at high Reynolds number down an inclined plane under the action of longitudinal magnetic and lateral electrical fields. Using energy integral method the problem is described with a third order dynamical system. The dynamical system can undergo two generic bifurcations, heteroclinic and Hopf bifurcations. The first bifurcation manifests as hydraulic jump while the second one gives birth to periodic wave. Via numerical integrations, we have shown that the electrical field can amplify or counterbalance the stabilizing effect of longitudinal magnetic field. When the electrical field is oriented toward the fluid interior, it augments the stabilizing effect of magnetic field. However, when the orientation of the electrical field is reversed, the electrical field overpowers the stabilizing effect of the magnetic field, and thus destabilizes the flow.

Importance of new magnetic field analysis for interface phenomena of ferromagnetic fluid

10727
Tue·14:50·4

Yo Mizuta
Hokkaido University, Japan

After the consideration that the interface phenomena of ferromagnetic fluid is quite delicate to the magnetic field, a rigorous magnetic analysis for arbitrary interface profile and applied magnetic field distribution is proposed. The dynamics based on Bernoulli's equation with the dynamic boundary condition requires only the interface magnetic fields. Thus, they are decomposed into the basic and the induced part, and the induced part is obtained from a set of simultaneous integral equations called three-dimensional interface magnetic field equations (IMFE), which are derived from the harmonic properties and the interface conditions. The IMFE is solved through the series of periodic functions of interface magnetic fields. The expansion coefficients as the wavenumber spectra are obtained from a set of linear equations. Effects of the interface profile changing like a hexagonal lattice on the basic field applied as a ridge-like distribution are investigated.

Equilibrium and stability in relaxed magnetohydrodynamics of toroidal plasmas

10491
Thu·09:15·8

Robert Dewar,[†] Matthew Hole, Mathew McGann, Ruth Mills and Stuart Hudson
The Australian National University, Australia[†]

The calculation of three-dimensional magnetohydrodynamic (MHD) toroidal plasma equilibria is a challenging one conceptually because of the problems of Hamiltonian field-line chaos and singular currents. Combined with the need to achieve high accuracy for plasma stability calculations, this makes the problem very difficult, but important for advanced fusion experiments. A new approach

based on multiple relaxed regions separated by ideal-MHD toroidal barrier tori is presented. This is cast as a variational principle, with the second variation giving necessary stability conditions for both ideal MHD and resistive MHD (in the limit of small resistivity).

Magnetic field reversals in nature, experiments and simulations

10869
Thu·09:35·8

Andre Giesecke,† Gunter Gerbeth and Frank Stefani
Forschungszentrum Dresden, Germany†

From paleomagnetic observations, numerical simulations and—meanwhile—also experiments, it appears that reversing dynamos are a quite common phenomenon. Long time series of mean field simulations adopting Earth-like parameters yield reversal sequences whose statistical behavior is comparable to the Earth. Recent hints for a reversing experimental dynamo give reason for the examination of a cylindrical dynamo with simulations that are especially suited to the experimental conditions. This requires a numerical scheme that is able to treat insulating boundary conditions and material properties like permeability and/or conductivity jumps. Preliminary calculations including a high permeability zone show a slight reduction of the critical Reynolds number. In future simulations permeability jumps will be increased and an α-effect describing the inductive action of turbulence will be included.

Investigation of interface oscillations in liquid metals using magnetic field tomography

11227
Thu·09:55·8

Christian Resagk,† Shouqiang Men, Hartmut Brauer and Marek Ziolskowski
Ilmenau University of Technology, Germany†

In this study, we apply magnetic field tomography (MFT) to measure the magnetic field induced by an electrical current near a cylindrical cell so as to reconstruct the displacement of the oscillating interface. Two electrically conducting fluids, KOH aqueous solution and GaInSn liquid alloy, are utilized in the depth ratio of 1:1. The interface modes are generated by vertical vibrations of a shaker. A CCD camera is used to record the interface oscillation and measure the displacement. Since the interface mode is non-axisymmetric, when a electrical current is applied to the electrodes of the cell, the radial and axial components of the magnetic flux density can be detected by a fluxgate-sensor-ring consisting of 16 two-dimensional sensors. The interface has been successfully reconstructed from the measured magnetic field data using dominant mode approach and is in a good agreement with the independent optical measurements.

Dissipation bounds for dynamos

11824
Thu·10:15·8

Thierry Alboussière
CNRS, LGIT Grenoble, France

Above dynamo threshold, magnetic energy grows and so does Joule dissipation. But can we assign an upper bound to dissipation in the full saturated regime? This question is addressed for Couette-type dynamos and a rigorous answer is provided in the framework of variational turbulence, following the Hopf–Doering–Constantin background method. For a prescribed velocity shear, it is possible to determine an upper bound for dissipation, even when dynamo action is present. For fluids with low P_m, it is found that dissipation cannot significantly exceed the classical (non MHD) scaling law until $R_m \sim P_m^{-1}$. At larger R_m, the bound for dissipation follows a larger scaling law. Now, when electrically conducting walls are considered, these findings change completely and dissipation can exceed the hydrodynamical scaling for moderate R_m numbers. The upper bound is even found to diverge at a finite value of R_m.

The helical magnetorotational instability in cylindrical Taylor–Couette flow

11858
Thu·16:00·3

Rainer Hollerbach,† Frank Stefani, Gunter Gerbeth, Thomas Gundrum and Gunther Rudiger
University of Leeds, UK†

We present new results from the PROMISE experiment, consisting of a GaInSn alloy confined between differentially rotating cylinders, in the presence of a combined axial and azimuthal (helical) magnetic field. The apparatus has been upgraded to incorporate split-ring end-plates, thereby reducing end-effects. The resulting traveling-wave disturbances are in good agreement with theoretical predictions for the onset of the helical magnetorotational instability.

The helicities and group velocities of unstable modes generated by tidal effects

11323
Thu·16:20·3

Krzysztof Mizerski,† Konrad Bajer and Keith Moffatt
University of Leeds, UK†

We address the question of a possibility of a dynamo generated by tidal effects (elliptical instability) at a very preliminary stage. In the limit of small elliptical deformations of a circular flow (weak tidal deformations of a rotating planet or star), in the presence of external magnetic field, we calculate the growth rates of main unstable resonant modes and for each resonance type we calculate the helicities and the group velocities. It turns out that only the mixed type resonance, between the hydrodynamic and magnetic modes leads to non-zero helicity and group velocity in the leading order. We complete the asymptotic considerations with calculating the helicities and group velocities of 'horizontal modes' (which propagate in the vertical direction and for which the velocity and the magnetic field lie in the horizontal plane) and a full numerical analysis of stability of elliptical flow in the presence of the magnetic field together with the Coriolis force.

Turbulent MHD channel flow with spanwise magnetic field

10715
Thu·16:40·3

Thomas Boeck,† Dmitry Krasnov, Oleg Zikanov and Joerg Schumacher
Techniche Universität Ilmenau, Germany†

We study turbulent channel flow of an electrically conducting liquid with a homogeneous magnetic field imposed in the spanwise direction. The Lorentz force is modelled using the quasistatic approximation. Direct and large-eddy simulations are performed for hydrodynamic Reynolds numbers $Re = 10000$ and $Re = 20000$ and the Hartmann number varying in a wide range. The main effect of the magnetic field is the suppression of turbulent velocity fluctuations and momentum transfer in the wall-normal direction. This leads to drag reduction and transformation of the mean flow profile. The centerline velocity grows, the mean velocity gradients near the wall decrease, and the typical horizontal dimensions of the coherent structures enlarge upon increasing the Hartmann number. Comparing the results from direct and large-eddy simulations we show that the dynamic Smagorinsky model accurately reproduces the flow transformation.

FM15 :: Microfluidics

Chairs: Carl Meinhart (USA) and Henrik Bruus (Denmark)

Thu	11:00–12:40	Room 10	Lectures
Thu	14:35–15:05	Hall D	Seminars
Thu	16:00–17:00	Room 8	Lectures

Semi-automated manipulation of crystals using acoustic fields and microfluidics in micromachined devices

10923
Thu·11:00·10

Stefano Oberti,† Jürg Dual, Adrian Neild, Sascha Gutmann and Dirk Möller
Institute of Mechanical Systems - ETH Zurich, Switzerland†

For the investigation of their spatial structure by means of X-ray crystallography, biological macromolecules (e.g. insulin crystals) are individually removed from the solution in which they grew using nylon loops. As this process is repeated for a large number of crystals there are efforts to automate it. As a novel approach, the combined use of acoustic manipulation and microfluidics is presented here. Acoustic radiation forces arise as a time averaged nonlinear effect from the interaction between a particle suspended in a fluid and acoustic waves propagating within that fluid. These forces have been identified as a useful way of concentrating particles into planes by resonant excitation of a fluidic cavity. Here, crystals are collected along the centerline of a microfluidic channel, moved towards an orifice by applying a fluid flow and removed using a loop. Design and operation are discussed by means of FE simulations supported by experimental data.

Microflow induced by Opercularia Assymetrica: optical experimental investigations

11866
Thu·11:20·10

Bogumila Zima-Kulisiewicz,† Antonio Delgado and Cornelia Rauh
Friedrich-Alexander University, Germany†

Microflow induced by Opercularia assymetrica living on Granular Activated Sludge (GAS) is investigated. GAS due to high density, ellipsoidal form with length up to 5 millimetres, high settling ability has a great application potential in biological purification of wastewater. However, granulation is a complex process and its mechanism is not fully understood yet. Additionally to biochemical and fluid dynamical factors in macro scale also characteristic microorganismic flow generated by cilia beats of Opercularia Asymmetrica in micro scale should be taken into account. Thus, in order to visualize micro flow in biological system micro Particle Image Velocimetry investigations with bio seeding particles are carried out. Obtained micro Particle Image Velocimetry results indicate existence of two characteristic vortices generated by single protozoa. Furthermore, the number of ciliates as well as seeding particles concentration have significant influence on the flow pattern.

Computational study of a novel valve mechanism for synthetic jet actuator

11906
Thu·11:40·10

Victoria Timchenko,† Chin Pang, Dan Li, Victoria Timchenko, John Reizes and Eddie Leonardi
The University of New South Wales, Australia†

An opening-closing valve mechanism for a synthetic jet actuator connected to the micro-channel etched at the rear side of the silicon wafer has been simulated in order to investigate the effects of such a configuration on the cooling of microchips with channels filled with water. The valve mechanism is designed to reduce the jet actuator cavity temperature by preventing the influx of heated fluid, and to allow the intake of relatively cold water from the supply, so that heat transfer rate between the microchip and the fluid is enhanced and the maximum temperature in silicon wafer is reduced. Instantaneous temperature distributions in silicon and the fluid as well as velocity fields in the channel were calculated by using the commercial package, ANSYS CFX 11.

Numerical studies of nonlinear kinetics in induced-charge electro-osmosis

10528
Thu·12:00·10

Henrik Bruus,† Martin Bazant and Misha Gregersen
Technical University of Denmark, Denmark†

We present a numerical study of induced-charge electro osmosis (ICEO) of electrolytes in microfluidic channels containing a fixed dielectric structure. ICEO is the nonlinear electro-osmotic slip that occurs in the electrolyte when an applied electric field acts on the ionic charge it induces around the polarizable surface of the dielectric structure. We also establish a method for optimizing the shape of the dielectric structure for any given objective function, e.g. the resulting pumping velocity achieved for asymmetric structures.

Non-local transport in nanofluids: k-space and real-space viscosity kernels

10794
Thu·12:20·10

Ruslan Puscasu,† Peter Daivis and Billy Todd
Swinburne University of Technology, Australia†

Classical Navier–Stokes–Fourier hydrodynamic theory adequately describes the rheological properties of the fluid at the scale lengths of the confinement much greater than the dimension of the fluid molecules. Once the confinement approaches molecular dimensions, classical theory must be generalized to allow for local position dependent coefficients. We present an analysis of the exact homogeneous nonlocal viscosity kernels for unconfined fluids for a variety of state points. This allows using nonlocal generalization of the linear constitutive relation with appropriate boundary conditions to predict the flow profiles for highly confined fluids. We compute the k-space and real-space kernels for atomic and molecular fluids calculated from the stress autocorrelation functions and the transverse momentum density autocorrelation functions. The results show that the kernels have a width of a few atomic diameters which means that the generalized hydrodynamic viscosity must be corrected.

The efficiency of the coupled electrode-membrane processes in hydrogen fuel cell: thermodynamic analysis

10158
Thu·14:35·D

Frantisek Marsik† and Tomas Nemec
Institute of Thermomechanics CAS, Czech Republic†

Gas diffusion electrodes, catalyst layers and diffusions of protons and water trough the proton exchange membrane (PEM) are analyzed from the irreversible thermodynamics point of view. Our description is based on a set of two mass balance equations (in 1D approximation) involving water and proton transport through the membrane, which are coupled with electrochemical reactions at the surfaces of electrodes. One couple of chemical reactions describes the Redox processes in fuel (Hydrogen-Oxygen) and the second couple of reactions characterizes the catalytic activity of Platinum. The attempt to analyze the whole membrane-electrodes assembly (MEA) of the fuel cell is presented. In terms of our simplified model the optimal coupling between water diffusion and electro-osmotic flux in PEM and corresponding maximum efficiency of a fuel cell are derived. Moreover, in the framework of accepted approximation the relations for the characteristic thickness of a PEM membrane can be calculated.

Gas flows through shallow non-uniform microchannels

11280
Thu·14:40·D

Amir Gat,† Daniel Weihs and Itzhack Frankel
Technion - Israel Institute of Technology, Israel†

We study the viscous compressible flow through shallow micro-channels (whose gap width is small in comparison with the other characteristic dimensions) of non-uniform cross section. A lubrication approximation is applied which reduces the viscous compressible slip-flow problem to a Neumann problem for a quadratic function of the pressure. Focusing on a symmetric constricted channel we obtain an analytic solution by means of a Schwartz–Christoffel transformation. This solution is verified by examining the convergence with diminishing Reynolds number and gap width of finite-element numerical simulations. Expressions for the pressure-head and mass-flow-rate losses in terms of the geometrical parameters characterizing the constriction are obtained, discussed in view of experimental data in the literature.

Dewetting of nanometer thin films under an electric field

11287
Thu·14:45·D

Guo-Hui Hu,† Ai-Jin Xu and Zhe-Wei Zhou
Shanghai Univeristy, China†

The dewetting of a thin water film under a nanoscale electric field is studied with molecular dynamics simulation. Results show that the development of small disturbance leads to the onset of film rupture. And the rim of the film recedes with a dynamic contact angle. Our transient streamlines indicate that liquid molecules near the rim moves almost vertically upwards, due to the repulsive force of the solid surface. The analyses of the wetting dynamics demonstrate that the applied electric field will increase the wettability of graphite walls, thus suppress the rupture, reduce the dynamic contact angle, and raise liquid density adjacent to both solid and free surface. The positive voltage has stronger influences than the negative one.

On penalty approaches for Navier-slip and other boundary conditions in viscous flow

11426
Thu·14:50·D

Yvonne Stokes† and Graham Carey
The University of Adelaide, Australia†

The penalty concept and associated techniques are extended to treat partial slip, free surface, contact and related boundary conditions in viscous flow simulation. In particular, we analyse the penalty partial-slip formulation and relate it to the classical Navier slip condition. Such boundary conditions are becoming increasingly important in consideration of near-wall effects for viscous flow in micro and nanofluidic applications and in upscaling from microscale behaviour to macroscale boundary conditions. Variants of the same penalty scheme also allow partial penetration through a boundary and, hence, the implementation of porous wall boundaries with leakage or ‘blowing and suction’, as well as free surface conditions. Using an algorithm that updates the flow geometry and penalty parameters over time enables the handling of moving contact line problems as well as time-varying boundary conditions as illustrated in numerical simulation studies.

Capillary driven flows: velocity dependent contact angles and chemically patterned walls

11701
Thu·14:55·D

Mihail Popescu† and John Ralston
University of South Australia, Australia†

The dynamics of penetration or depression of liquid into homogeneous narrow tubes due to capillary pressure is well described by the Washburn equation. In this paper we consider capillary flow in the case when: (i) the contact angle is not constant and equal to the static (equilibrium) value, but rather variable and dependent on the velocity of the moving three-phase contact line, or (ii) the capillary tube has chemically patterned walls with alternating stripes made of two different materials. We show that in the first case the dynamics is qualitatively similar with that predicted by the Washburn equation, while in the second case significantly new qualitative features occur, e.g., a stick-slip like behavior.

Hydrodynamic friction of a polymer adsorbed on a planar surface

11890
Thu·15:00·D

Krzysztof Sadlej,† Maria Ekiel-Jezewska and Eligiusz Wajnryb
Polish Academy of Science, Poland†

A rigid polymer model consisting of two identical spherical particles, irreversibly adsorbed on a planar channel wall is considered. The linear dimensions of the polymer are assumed to be small enough to validate an expansion of the flow inside the channel to linear terms only. The polymer is therefore effectively immersed in a shearing flow. Total hydrodynamic force acting on the polymer is calculated. The dependence of that force on the polymers orientation is derived taking into account symmetries of the system. Large differences in the force are found for different polymer orientations. Applications of these results are sketched.

Controlled cavitation and sonoporation in microfluidics

12209
Thu·16:00·8

Pedro Quinto Su,† Claus-Dieter Ohl, Séverine Le Gac, Albert van den Berg, Ed Zwaan and Kinko Tsuji
Researcher, Singapore†

Cavitation—the growth and collapse of mostly empty bubbles—is commonly attributed to large scale and very rapid flows, e.g. at ship propellers or at fuel injection nozzles. Only recently the attention from largely free cavitation bubbles has shifted towards the study of more confined bubbles. Here we report on an experiment to exploit cavitation in microfluidic systems or so called lab-on-a-chip devices for flow handling and biological cell manipulation. In microfluidics generally due to the small scales low Reynolds number flows are observed. Yet, cavitation bubble induced flows allow to reach a high Reynolds number regime also on small scales. By exploiting this rarely studied flow regime new techniques for liquid and cell handling become feasible. Here, we will report first on the effect of a channel wall on the bubble dynamics, discuss pumping, and then present an application for cell handling and plasma membrane poration.

Free surface microfluidics for explosives detection

12199
Thu·16:20·8

Brian Piorek,[†] Carl Meinhart, Seung Lee, Lisan Viel, Sanjoy Banerjee and Martin Moskovits
University of California, Santa Barbara, USA[†]

A novel microfluidic, chemical detection platform has been developed for real-time sensing of airborne agents. The key enabling technology is a newly developed concept termed Free-Surface Fluidics (FSF), where one or more fluidic surfaces of a microchannel flow are confined by surface tension and exposed to the surrounding atmosphere. The result is a unique open channel flow environment that is driven by pressure through surface tension, and not subject to body forces, such as gravity. Evaporation and flow rates are controlled by microchannel geometry, surface chemistry and precisely-controlled temperature profiles. The free-surface fluidic architecture is combined with Surface-Enhanced Raman Spectroscopy (SERS) to allow for real-time profiling of atmospheric species and detection of airborne agents. The results indicate that airborne explosive agents such as DNT, TNT, RDX, TATP can be readily detected.

Fabrication of a nanofluidic field effect transistor for controlled cavitation in nanochannels

11932
Thu·16:40·8

Egbert van der Wouden,[†] Johan Bomer, Jan Eijkel, Sumita Pennathur and Albert van den Berg
University of Twente, Netherlands[†]

In this paper, we outline the fabrication process of a Nanofluidic Field Effect Transistor (NFFET), which consists of a sequence of novel photolithography, etching and deposition steps. A NFFET is a nanofluidic device with which we can modify local surface charges by the application of a gate potential. This modification results in difference in the magnitude and direction of electroosmotically driven flow. Using applied gate potentials to change local surface charge, we can induce local pressure differences in the nanofluidic channel to create cavitation. We show initial modelling results that indicate the possibility of cavitation in devices as high as 50 nm.

FM16 :: Microgravity fluid mechanics

Chairs: Wenrui Hu (China) and Hans Rath (Germany)

Tue	10:40–12:40	Room 10	Lectures
Tue	14:00–14:40	Room 4	Seminars

Boiling heat transfer in microgravity

10803
Tue·10:40·10

Jian-Fu Zhao† and Shi-Xin Wan
Chinese Academy of Sciences, China†

Two research projects on pool boiling in microgravity have been conducted aboard the Chinese recoverable satellites. Ground-based experiments have also been performed both in normal gravity and in short-term microgravity in the Drop Tower Beijing. Steady boiling of R113 on thin platinum wires was studied with a temperature-controlled heating method, while quasi-steady boiling of FC-72 on a plane plate was investigated with an exponentially increasing heating voltage. In the first case, slight enhancement of heat transfer is observed in microgravity, while diminution is evident for high heat flux in the second one. Lateral motions of bubbles on the heaters are observed before their departure in microgravity. The surface oscillation of the merged bubbles due to lateral coalescence between adjacent bubbles drives it to detach from the heaters. It's also discussed about the Marangoni effect on the bubble behavior.

Vibration-induced Rayleigh instability in supercritical fluids under microgravity conditions

11201
Tue·11:00·10

Daniel Beysens† and Sakir Amiroudine
Ecole Supérieure de Physique et de Chimie Industrielles, France†

Supercritical fluids are very compressible and expandable near their critical point. Then even minute temperature inhomogeneities can cause large density gradients. It has been experimentally observed that fluids (CO_2, H_2) placed in such conditions under weightlessness and submitted to low amplitude (e.g. 0.3 mm), high frequency vibrations (e.g. 20 Hz) can exhibit very particular behaviour. In particular, the thermal boundary layer created near a boundary during a temperature change can be destabilized and exhibits periodic fingering perpendicular to the vibration direction. In order to study this instability, numerical simulations are performed of supercritical CO_2 (Newtonian, compressible, viscous, conducting heat and expandable) in a non stationary state. The Navier–Stokes equations coupled with the energy and state equations and with the initial and boundary conditions are solved with a finite volume method in a staggered mesh. The equation of state is linearized.

Capillary channel flows

11302
Tue·11:20·10

Michael Dreyer,† Joerg Klatte and Aleksander Grah
University of Bremen, Germany†

This paper is concerned with steady and unsteady flow rate limitations in open capillary channels under low gravity conditions. Capillary channels are widely used in space technology for liquid transportation and positioning, e.g. in fuel tanks and life support systems. The channel, observed in this work, consists of two parallel plates bounded by free liquid surfaces along the open sides. The flow through the channel is forced by a pump. Increasing the flow rate in small steps causes a decrease of the liquid pressure. A maximum steady flow rate is achieved when the collapse of the free surfaces occurs. In the case of unsteady flow additional dynamic effects take place due to flow rate transition and liquid acceleration. The maximum flow rate is smaller than in the case of steady flow. On the other hand, the choking effect does not necessarily cause surface collapse and stable, temporarily choked flow is possible under certain circumstances.

Experiments on aqueous foams in microgravity: a way to study poroelastic effects in soft wet cellular materials

11335
Tue·11:40·10

Arnaud Saint-Jalmes,† Dominique Langevin and Sebastien Marze
Centre National de la Recherche Scientifique, France†

For many biological tissues, the coupling between macroscopic deformations and the diffusion of the interstitial fluid (known as "poroelasticity") is expected to be an important ingredient of the mechanical response. We show that an aqueous foam, once gravity-driven drainage is removed, can be used to study how pressure gradients in a interstitial fluid diffuse inside a cellular soft structure. In that respect, we report results of imbibition experiments performed in parabolic flights and in rockets. Different setup, imbibition modes and bubble surface mobilities are studied. Foams with high liquid fractions can be obtained; a theoretical description is presented especially explaining that at high liquid fractions the dependance on the interfacial mobilities vanishes. These results allows us to better understand the swelling or shrinking of soft materials induced by interstitial liquid motion. We also present results on how unstable foams on Earth behave in low gravity.

The capillary flow experiments aboard ISS: weakly 3D interior corner flows

11523
Tue·12:00·10

Mark Weislogel† and Ryan Jenson
Portland State University, USA†

The Capillary Flow Experiments (CFE) are performed aboard the International Space Station (ISS) during Increments 9 to 16 (August 2004 to December 2007). In this work, preliminary results from both flight and drop tower experiments are reported for spontaneous capillary driven flows in tapered polygonal containers. The results are employed to benchmark concurrent theory which aids in the design and analysis of capillary devices such as 3D vane networks for bubble-free collection and positioning of fuels for satellites, an important problem concerning propellant and/or cryogenic liquid management aboard spacecraft.

Reduced gravity testing and research capabilities at Queensland University of Technology's new 2.0 second drop tower

12008
Tue·12:20·10

Ted Steinberg
Queensland University of Technology, Australia

Reduced gravity experimentation is important to investigate fundamental and applied aspects of diverse physical phenomena. Few experimental facilities are available that allow researchers access to reduced gravity environments. The Queensland University of Technology has recently fabricated a purpose built, stand alone 2.0 second drop tower to permit reduced gravity experimentation. The specifications and operation of this facility are presented. Current areas of research include fluid dynamics and multiphase flow, nanomaterial production including silica sol-gels and carbon nanotubes, and heterogeneous combustion with a focus on bulk metallic materials burning in oxygen enriched atmospheres (in collaboration with NASA). Discussion on the use of the new research facility in the production of advanced materials for earth-based applications will be presented. Opportunities will also be discussed regarding both collaborative research and the provision of reduced gravity test services.

Behaviour of drops and bubbles in non-uniform pulsational flows

10175
Tue·14:00·4

Tatyana Lyubimova,† Alexandra Cherepanova and Dmitriy Lyubimov
Institute of Continuous Media Mechanics UB RAS, Russia†

The behaviour of a drop or bubble suspended in a fluid subjected to the non-uniform pulsational field is studied for zero gravity conditions. It is shown that under high frequency vibrations the drop is affected by the average force which is directed along the average density gradient of the pulsational flow kinetic energy. For interaction of the drop (bubble) with oscillating wall it is found that in the case of low viscous host fluid the attraction of the drop to the wall takes place and with the growth of viscosity, at small distances from the wall, the effect changes its sign, however for large distances the attraction effect is maintained. The mechanism of this phenomenon is discussed. The interaction of two drops (bubbles) is studied. It is shown that for vibrations parallel to the centers line, at large distances there takes place repulsion and at small distances—attraction and for vibrations perpendicular to the centers line the situation is opposite.

Viscosity measurement via drop coalescence: a space station experiment

10837
Tue·14:05·4

Basil Antar,† Edwin Ethridge and Nobuhisa Yasuda
University of Tennessee Space Institute, USA†

The concept of using low gravity experimental data together with CFD simulations for measuring the viscosity of highly viscous liquids was recently validated on onboard the International Space Station (ISS). A series of microgravity tests were conducted for this purpose on the ISS in July, 2004 and in May of 2005. In these experiments two liquid drops were brought manually together until they touched and were allowed to coalesce under the action of the capillary force alone. The coalescence process was recorded photographically from which the contact radius speed of the merging drops was measured. The liquid viscosity was determined by fitting the measured data with accurate numerical simulation of the coalescence process. Several liquids were tested and for each liquid several drop diameters were employed. Experimental and numerical results will be presented in which the viscosity of several highly viscous liquids were determined using this technique.

Planar migration of two drops in a thermal gradient

10866
Tue·14:10·4

Ren Sun
Shanghai Jiao Tong University, China

A theoretical exploration is performed on the migration of two drops in another liquid subjected to arbitrarily-combined gravitational field and imposed thermal gradient in the case of vanishingly small Re and Ma. Accurate migration velocities of two drops in the planar motions are derived using newly-introduced successive partial reflections and extended successive reflections. The complete velocity expressions can be reduced to the two well-known YGB ones as s approaches infinity and correspond to those given by Sun and Hu (Phys. Fluids 15(10), 3015, 2003) by letting gravitational acceleration, thermal conductivities and viscosities of the drops turn to zero. As a corollary, two equal-sized drops with the same internal liquid in a microgravity environment have to migrate at an identical velocity which is dependent on the separation distance between them and the ratio of the thermal conductivity of the drop phase to that of the continuous phase.

Numerical simulations of drop thermocapillary migration with variable viscosities

11435
Tue·14:15·4

Zhaohua Yin,† Wenrui Hu and Peng Gao
Chinese Academy of Sciences, China†

In this paper, the problem of drop thermocapillary migration under the micro-gravity condition is investigated numerically. The main focus is the effect of variable kinetic viscosity in the migration process. When the changing rate of viscosity is small, the time evolution of drop migration speed shows almost no difference from those of constant viscosity runs, and the drop eventually reaches a steady migration speed. When the changing rate of viscosity is large enough, the migration velocity of the drop could not reach the equilibrium. The factors that influence the viscosity changing rate are discussed and analyzed.

Effect of an eccentric rotation on the equilibrium shapes and stability of liquid bridges in a lateral gravity field

11621
Tue·14:20·4

Ana Laverón,† Victoria Lapuerta, Angel Rodríguez and Jose Perales
Universidad Politécnica de Madrid, Spain†

A cylindrical liquid bridge supported between two circular-shaped disks in isorotation is considered. The combined effect of a lateral gravity field and an offset between the rotation axis and the axis of the supporting disks (eccentricity) on the stability of the liquid bridge is here studied. In a previous work a numerical method used to determine the stability limit for different values of eccentricity was validated by comparing with analytical results at small eccentricity. In this work we use an extension of that algorithm applied to liquid bridges in a lateral gravitational field rotating around an eccentric axis to study the combined effect of rotation, eccentricity and lateral gravity. The analysis shows that the combined effect of lateral gravity and eccentricity can narrow or broaden the stability region depending on the angle between the gravity direction and the eccentric displacement.

Stability analysis of thermocapillary convections in liquid bridges with Prandtl number of 100 under microgravity

11733
Tue·14:25·4

Qi-Sheng Chen† and Ya-Chao Liu
Chinese Academy of Sciences, China†

Linear stability analysis has been performed to investigate the effect of liquid volume on the onset of the oscillatory convection in liquid bridges with Prandtl number of 100. The steady axisymmetric basic state was obtained by solving the 2D governing equations by the spectral method. 3D perturbation equations were then discretized using the Chebyshev-collocation method. The eigenvalues and eigenfunctions were obtained by using the QR method. For calculation of the 2D basic-state fields, we used 49×97 Chebyshev polynomials in r and z directions, respectively, while we used 33×33 Chebyshev polynomials for solving the perturbation equations. For slender liquid bridges, the thickness of the velocity boundary layer is around 1% of the height of the liquid bridge at the transition point. For fat liquid bridges, the thickness of the velocity boundary layer is around 0.1% of the height at the transition point.

Effect of microgravity on interface shape: simulation using smoothed particle hydrodynamics

11737
Tue·14:30·4

Arup Das† and Prasanta Das
Indian Institute of Technology, Kharagpur, India†

A 2D cylindrical numerical model based on smoothed particle hydrodynamics was developed to simulate the interfacial behavior of multiphase flow problem under microgravity condition. Surface tension force based on continuum surface force method is added in momentum equations to track the exact shape of the interface of multi phase mixtures. To prevent abrupt mixing of the fluids and shooting of one type of particles into other due to insertion of microgravity, no penetration force is applied for two closely situated fluid particles of different type. Solid walls at the periphery of the multiphase flow mixture are modeled with two layer of virtual particle along the boundary. To validate the present numerical model for multiphase flow under microgravity condition different case studies like bubble evolution under microgravity condition etc. has been examined with considerable accuracy.

Mass transfer in supercritical carbon dioxide

11845
Tue·14:35·4

Rainer Benning,† Özgür Ertunc and Antonio Delgado
University Erlangen-Nuremberg, Germany†

Although extraction with supercritical fluids is a common technique, elaborated knowledge of the governing processes is missing in some cases although it is necessary to optimise an industrial scale process with respect to product yield. Similar considerations hold for the process of nucleation. To close such knowledge gaps the diffusion and the nucleation of selected substrates in supercritical carbon dioxide are investigated. Experiments will be carried out in earth laboratory as well as under compensated gravity. The results of both approaches will be used to determine and separate the governing parameters with and without convection. Additionally, modelling approaches for the diffusion process on the basis of cognitive algorithms will be prepared to be developed at a later stage. In the presented project parabolic flight experiments will be utilised to design the experimental setup and to define the necessary parameter ranges for long term campaigns on board the ISS.

FM17 :: Solidification and crystal growth

Chairs: Gustav Amberg (Sweden) and Grae Worster (UK)

Thu	11:00–12:40	Room 6	Lectures
Thu	14:40–14:55	Room 1	Seminars

Heterogenous nucleation and successive microstructure evolution during solidification

10245
Thu·11:00·6

Heike Emmerich
RWTH Aachen, Germany

It is well known, that the mechanical properties of a material sample after solidification are strongly tied to its microstructure. Nevertheless, the precise laws governing the initial stage of this structuring process—i.e. nucleation, in particular heterogenous nucleation—are still not fully understood. Here we show, that the phase field method, which originally established itself to tackle the free boundary problem given by microstructure evolution, can also be employed to investigate the energetics of heterogenous nucleation in a solidifying sample. Based on this approach, simulation results establishing new relations between processing conditions and nucleation rates during primary phase transition on the one hand, and nucleation rates and mechanical properties for secondary phase transformation on the other, are presented.

Asymptotic results for a Stefan problem with surface tension

10802
Thu·11:20·6

Scott McCue,† Bisheng Wu and James Hill
Queensland University of Technology, Australia†

We consider here the two-phase Stefan problem that arises from modelling the melting process of a spherical particle. Surface tension is included through the Gibbs–Thomson condition, the effect of which is to reduce the melting temperature as the particle radius decreases. We discuss the asymptotic limits of slow conduction in the solid phase and large ratio of latent heat to specific heat. Further, we present numerical results that suggest for later times superheating develops in the solid phase, followed by a form of finite-time blow-up, with both the temperature gradient at the solid-melt interface and the interface speed becoming unbounded before complete melting takes place.

Steady-state solidification of aqueous solutions in a new directional solidification facility

11388
Thu·11:40·6

Herbert Huppert,† Grae Worster and Stephen Peppin
University of Cambridge, UK†

A new facility is described which has been developed to investigate the directional solidification of transparent aqueous solutions forming mushy layers and chimneys in a quasi-two dimensional system. Experiments have been conducted on solutions of sodium chloride and ammonium chloride by translating a Hele–Shaw cell at prescribed rates between fixed heat exchangers. Regime diagrams have been found quantifying the morphological transitions induced as a function of freezing rate and the initial concentration of the solution. A small region in velocity-concentration parameter space was found within which uniform mushy layers can be grown. Outside this region defects occur either in the form either of chimneys or as the growth of secondary crystals.

Experimental compaction in a crystallizing mushy zone

11795
Thu·12:00·6

Renaud Deguen,† Jean-Paul Masson, Patrick La Rizza, Daniel Brito and Thierry Alboussière
Université Joseph Fourier, France†

The Earth inner core has been slowly crystallizing from the outer core for 1 or 2 Gy, powering convection in the outer core by releasing latent heat and light elements. Theoretical models predict the formation of a very thick mushy layer at the inner-outer core boundary where convection and compaction are expected to play key roles. Geophysically relevant questions include: how much liquid can be trapped in the inner core? What are the effects of compaction on the thickness of the convecting zone? on the existence and structure of chimneys? We have designed and build an experiment devoted to the study of compaction during the dendritic crystallization of a model material. In our experimental set-up, compaction is promoted by a high apparent gravity, which is imposed by putting the crystallizing sample in a standard lab centrifuge, where the centrifuge acceleration can reach $2000g$. This device also allows the study of thermochemical convection at low Ek and high Ra.

Modelling the growth and motion of a free dendrite under terrestrial conditions

11252
Thu·12:20·6

Minh Do-Quang† and Gustav Amberg
Royal Institute of Technology, Sweden†

Growth of a free dendritic crystal from an undercooled pure melt influenced by gravity was studied by using a semi-sharp phase-field method. The motion of the solid dendrite is simulated by using the fictitious domain method. The growth of the dendrite is influenced by convective heat transfer as it settles through the slightly less dense melt, and the evolution of the shape is thus coupled to the motion of the crystal. The model was formulated using two different meshes. One is a fixed background mesh, which covers the whole domain. The other is an adaptive mesh, where the node points are also translated and rotated with the movement of the solid particle.

Analytical prediction of solidification in close-celled metal foams

12210
Thu·14:40·1

Tongbeum Kim,† Tianjian Lu and Bin Zhang
Xi'an Jiaotong University, China†

Solidification often occurs during the processing of homogeneous/heterogeneous materials. It is at present possible to analytically predict the solidification behavior only for homogeneous (dense) materials using, for example, Neumann's solutions for Stefan problems. This paper introduces an analytical model capable of predicting the location of solidification front as well as the full solidification time for heterogeneous materials such as close-celled metallic foams. Full numerical simulations with the method of finite difference are conducted to validate the analytical model, and excellent agreement between analytical predictions and numerical calculations is achieved. The model predicts that an increase in porosity causes significant retardation of full solidification as a result of decreased effective thermal conductivity and diffusivity of the porous medium.

Nano-scale solidification phenomena

10046
Thu·14:45·1

Tomasz Kowalewski,[†] Justyna Czerwinska and Erwan Deriaz
Polish Academy of Sciences, Poland[†]

Solidification is highly complex multi-physics transition phenomena which is highly important for various industrial applications. Molecular Dynamics simulation offers a simple and comprehensive tool to understand the complex microscopic phenomena occurring in solidification process. We have been investigating solidification of one and multi component Lennard–Jones crystals growth. The numerical virtual solidification facility allows to study following properties: local order parameter to decide if the sample is fluid or solid, the formation of the nucleation sites, the orientation and order of the crystal structure, the velocity of the solidification front, the presence and characteristics of voids in the crystal structure, the deformation parameter, the elasticity and the shear/stress response of a material, the transport coefficients of the media including the self-diffusion coefficients and the viscosity of liquid performing solidification.

Phase-field simulation for the growth of boride (Fe2B) phase from austenite phase

10948
Thu·14:50·1

Raden Ramdan,[†] Tomohiro Takaki and Yoshihiro Tomita
Kobe University, Japan[†]

The present paper describes briefly the development of phase-field simulation for the growth of boride (Fe_2B) phase from the austenite phase. The main problem in developing this simulation works for Fe_2B compound is similar with the problem for a line compound that the derivative of free energy of this compound does not exist which is required for phase field simulations. In the present works, this problem is approached by an assumption that free energy has a parabolic relationship with concentration. Three sets of free energy were prepared and one set of free energy achieved the equilibrium condition for Fe_2B boride. On the other hand, evaluation of the effect of temperature on the growth of boride phase using the present model shows that a higher growth of boride phase was found as the temperature increases from 1193K up to 1273K

FM18 :: Stirring and mixing

Chairs: Stephen Cox (UK) and Nadine Aubry (USA)

Mon	16:25–17:45	Hall D	Lectures
Thu	15:00–15:05	Room 8	Seminars
Thu	16:00–17:00	Room 5	Lectures
Fri	11:00–12:00	Hall E	Lectures

Stretching and mixing of chemically reactive chaotic flows **11662** Mon·16:25·D

Paulo Arratia† and Jerry Gollub
University of Pennsylvania, USA†

In this talk, we investigate the effects of chaotic advection and diffusion on fast chemical reactions of the type $A+B \rightarrow 2P$ in two-dimensional fluid flows using i) experimentally measured stretching fields and ii) fluorescent monitoring of the local concentration. We show that flow symmetry, Reynolds number, and mean path length affect the spatial distribution and time dependence of the reaction product. Remarkably, a single parameter $\overline{\lambda}N$, where $\overline{\lambda}$ is the mean Lyapunov exponent and N is the number of mixing cycles, can be used to predict the time-dependent total product for flows having different dynamical features. We also explore the connection between the product concentration field and the stretching field. We observe that the lines of high past stretching (i.e. unstable manifold) usually correspond to regions of high product concentration.

Chaotic mixing in a helix-like pipe with periodic variations in curvature and torsion **10775** Mon·16:45·D

Mitsuaki Funakoshi† and Bongkyun Jang
Kyoto University, Japan†

The chaotic motion of fluid particles and fluid mixing by a steady three-dimensional flow through a helix-like circular pipe twisted around a circular or elliptic cylinder are examined numerically. The curvature and torsion of centerline of this pipe vary periodically. Fluid particles are moved in the cross-sectional direction by the combination of a rigid rotation due to the effect of torsion and the velocity in a pipe of constant curvature and zero torsion caused by an axial pressure gradient. Periodic variations in curvature and torsion cause chaotic motion of particles. In Poincaré sections of cross-sectional motion of particles, large chaotic region is observed for Reynolds number within a certain intermediate range, for pipes twisted around a thin elliptic cylinder, and for pipes twisted around a circular cylinder of small radius. We also confirm that mixing efficiency in a small number of periods is high in these cases.

Topological chaos in flows on surfaces of arbitrary genus **10000** Mon·17:05·D

Matthew Finn† and Jean-Luc Thiffeault
The University of Adelaide, Australia†

The emerging field of topological fluid kinematics is concerned with design and analysis of effective fluid mixers based on the topology of the motion of stirring apparatus and other periodic flow structures. Knowing even a small amount of flow topology often permits very powerful diagnoses, such as proving existence of chaotic dynamics and a lower bound on mixing measures based on material stretching. In this paper we present a canonical method for examining flows on surfaces of arbitrary genus given the flow topology encoded as a braid. The method may be used to study fluid mixing driven by an arbitrary number of stirrers in either bounded or spatially-periodic fluid domains. Additionally, and unlike previous techniques, the current work may also be applied to flows on manifolds of higher genus.

Tailoring chaotic mixing within a translating droplet by oscillatory rotation

11619
Mon·17:25·D

Rodolphe Chabreyrie,† Pushpendra Singh, Cristel Chandre, Dmitri Vainchtein and Nadine Aubry
Carnegie Mellon University, USA†

Tailored mixing inside individual droplets could be useful to ensure that reactions within microscopic discrete fluid volumes, which are used as microreactors in "digital microfluidic" applications, take place in a controlled fashion. In this article we consider a translating spherical liquid drop to which we impose a time periodic rigid-body rotation. Such a rotation not only induces mixing via chaotic advection, which operates through the stretching and folding of material lines, but also offers the possibility of tuning the mixing by controlling the location and size of the mixing region. Tuned mixing is achieved by judiciously adjusting the amplitude and frequency of the rotation, which are determined by using a resonance condition and following the evolution of adiabatic invariants. As the size of the mixing region is increased, complete mixing within the drop is obtained.

Chaotic thermal mixing in a two rod mixer

11391
Thu·15:00·8

Kamal El Omari† and Yves Le Guer
University of Pau, France†

We present a numerical study of chaotic advection used for the mixing and heating of highly viscous fluids in a two rod mixer. The boundaries of the mixer are kept at constant temperature, so they represent a heat source which is continuously dissipated in the 2D modulated flow. A global chaotic flow is necessary to prevent the formation of unmixed KAM islands (cold zones) and hot spots. The enhancement of heat transfer as well as the homogenization of the fluid temperature are found to be mainly dependent on the direction of the rods rotation, its period and on the rods eccentricity. The evolution of the standard deviation of fluid temperature and of its average, shows an exponential decay with time. This would indicate that the temperature field evolves into a complex self-similar pattern. This pattern arises from the interplay between stretching, folding and thermal diffusion. The PDFs of the rescaled temperature clearly confirm the presence of a strange eigenmode in the flow.

Speeding up mixing with moving walls

11203
Thu·16:00·5

Jean-Luc Thiffeault,† Emmanuelle Gouillart and Olivier Dauchot
University of Wisconsin—Madison, USA†

Mixing in viscous fluids is challenging, but chaotic advection in principle allows efficient mixing. In the best possible scenario, the decay rate of the concentration profile of a passive scalar should be exponential in time. In practice, several authors have found that the no-slip boundary condition at the walls of a vessel can slow down mixing considerably, turning an exponential decay into a power law. This slowdown affects the whole mixing region, and not just the vicinity of the wall. The reason is that when the ergodic mixing region extends to the wall, a separatrix connects to it. The approach to the wall along that separatrix is polynomial in time and dominates the long-time decay. However, if we move the walls closed orbits appear, separated from the bulk by a hyperbolic fixed point with a homoclinic orbit. The long-time approach to the fixed point is exponential, so we recover an overall exponential decay, albeit with a thin unmixed region near the wall.

The prevalence of ghost rods in batch mixer designs

10481
Thu·16:20·5

Stephen Cox† and Ben Binder
University of Nottingham, UK†

In batch mixers, rods are used to stir a fluid. If the motion of the rods describes a nontrivial mathematical braid, then certain desirable properties may be inferred regarding the stirring that correspondingly takes place in the fluid. It has been recognized that flow structures themselves (such as periodic islands) may play the role of proxy (or ghost) stirring rods, and that the additional consideration of the motion of these flow structures may shed light on stirring properties of the flow. Here we investigate the prevalence of such proxy stirring rods in some typical batch-mixer flows.

Advection of passive fluid by periodical injection from a two-dimensional flat chink

11003
Thu·16:40·5

Alexandre Gourjii,† GertJan van Heijst, Viatcheslav Meleshko and Luca Zannetti
Institute of Hydromechanics, NASU, Ukraine†

We examine the stirring processes by the two-dimensional flow of inviscid fluid generated by periodic injecting of fluid from a sharp chink in a flat wall into non-perturbed half-space. Low order models based upon classical discrete vortices embedded into an inviscid fluid are employed. The unsteady flow near the wall is modeled by a nascent point vortex of variable intensity satisfying the Kutta–Joukovskii condition during transient processes. Numerical results of simulations of the transport processes in the near-wall zone, the determination of regions of low and high domains of passive admixtures are discussed. A special technique for the quantitative estimate of the quality of stirring properties is given. Finally we compare numerical and analytical solutions with the results of analogue laboratory experiments.

Laminar mixing of fluids and scalars: a unified Hamiltonian approach

11461
Fri·11:00·E

Michel Speetjens† and Viatcheslav Meleshko
Eindhoven University of Technology, Netherlands†

Scalar transport fundamentally is the transport of “parcels” of a given scalar quantity by the total advective-diffusive scalar flux in an analogous manner as fluid motion is the transport of fluid parcels by the flow. This fundamental analogy between scalar transport and fluid motion admits application of Hamiltonian methods well-known from laminar mixing studies to laminar scalar transport. Key to these methods is description of fluid advection—and the mixing properties—in terms of the geometry of the fluid trajectories (“flow topology”). These Hamiltonian methods facilitate investigation of the geometry of the scalar trajectories (“scalar topology”)—and thus the scalar transport—in an entirely analogous manner. The unified Hamiltonian approach and its potential for investigation of laminar scalar transport is demonstrated by way of example.

Mixing of polymer solution in curvilinear pipe

11374
Fri·11:20·E

Shinji Tamano,[†] Motoyuki Itoh, Akira Sasakawa and Kazuhiko Yokota
Nagoya Institute of Technology, Japan[†]

The relation between the secondary flow pattern and the mixing of viscoelastic fluids in a curvilinear pipe was investigated using the flow visualization and the two-dimensional PIV measurement. The number of curves N was set at 1 and 60. As a viscoelastic fluid, polyacrylamide (PAA) solution of 0.1 wt% in water with the shear-thinning property was used. For Glycerin solution of 50% in water, the secondary flows at $N = 60$ for both Reynolds numbers of $Re = 50$ and 89 showed the fairly symmetrical pair of vortices with respect to the horizontal line at the exit of the test section. On the other hand, for PAA 0.1 wt%, two pairs of vortices were observed at $N = 60$ for $Re = 88$, while only one pair of vortices were observed at $Re = 50$ like Glycerin 50 %. It was found that this drastic change of the secondary flow pattern resulted in the promotion of fluid mixing at $N = 60$ for PAA 0.1 wt%.

Stirring with ghost rods in counter-rotating flows

10150
Fri·11:40·E

Mark Stremler[†] and Jie Chen
Virginia Tech, USA[†]

Two-dimensional, time-periodic flows can contain regions of both chaotic and integrable particle transport. When the objective is to mix the fluid, the intuitive assumption is to focus on eliminating integrable transport. However, there can exist periodic orbits in the flow that act as ‘stirring rods’, wrapping up and stretching out the surrounding fluid. The interactions of these ‘ghost rods’ can be sufficiently complicated to guarantee global chaotic behavior through application of the Thurston–Nielsen classification theorem, which establishes a quantitative lower bound on exponential stretching of non-trivial material lines in the flow. We examine the existence and characteristics of ‘ghost rods’ in two examples of counter-rotating flow and consider the role of these structures in determining an optimal mixing protocol.

FM19 :: Turbulence

Chairs: Fazle Hussain (USA) and Eberhard Bodenschatz (Germany)

Tue	14:00–14:50	Room 5	Seminars
Tue	15:00–15:10	Hall E	Seminars
Thu	09:15–10:35	Room 5	Lectures
Thu	11:00–12:40	Room 5	Lectures
Fri	09:15–10:35	Room 5	Lectures

A new look into re-effect on turbulent round jets

10206
Tue·14:00·5

Jamie Mi
Peking University, China

This paper investigates experimentally the effect of the initial velocity and diameter on the far-field mean velocity of a round jet. Present measurements were made in jets issuing from smooth contraction nozzles of two diameters ($D = 10$ mm and 50 mm) and also with different exit bulk mean velocities ($U_o = 1$ m/s ~ 72 m/s). Results are compared with previous data published by other researchers. It is shown that the inlet Reynolds number Re_o ($\equiv U_o D/\nu$, where ν is the kinematic viscosity) has a complex influence on the mean flow, with its critical value varying with D. The present work supports the observation of Malmstrom *et al.* that, as U_o increases from a low value (< 5 m/s), the mean velocity decay rate decreases until $U_o \approx 6$ m/s and becomes nominally constant at higher U_o.

Drag reduction of a deforming film covered with polysaccharide in turbulent water flow

11774
Tue·14:05·5

Yoshimichi Hagiwara,† Kousuke Takashima and Katsutoshi Sakurai
Kyoto Institute of Technology, Japan†

Direct numerical simulation has been conducted for turbulent water flow around a deforming film covered with polysaccharide (e.g. Carrageenan), in order to examine whether or not large blades of algae reduce the friction drag. The deformation of the film is assumed to be two-dimensional sinusoidal. The amplitude of the deformation is periodical. Since the amplitude of the deformation is low, the increase in the pressure drag is negligible. Polysaccharide, which covers the whole film surfaces, is simulated with layers of many beads. These beads are connected with springs and dashpots in the normal direction to the film surfaces. All the beads interact with flow. It is found that the film deformation and beads modify the coherent structures. This modification leads to decreases in the Reynolds shear stress and wall shear stress. Thus, the film deformation and polysaccharide are effective for the reduction of the friction drag acting on the film.

The growth rate in Rayleigh–Taylor instabilities by overturning experiment in tank

10501
Tue·14:10·5

Xi Li† and Vincent Chu
Hohai University, China†

The well observed Rayleigh–Taylor instability applies to the instantaneous mixing of density variable fluids, available data (Andrews & Spalding, 1990, Voropayev *et al.*, 1993, Li & Chu, 2005) shows uncertainty of the mixing width growth rate. Li & Chu (2005) has clarified the late stage of mixing front movement; dimensional analysis of data sets has recently shown new identity on mixing width growth by tracking mass center (Li & Chu, 2007), two stages of mixing width evolution appear: the early stage shows a quadratic relation, and late stage shows a linear relation. Based on the same experiments in Li & Chu, 2007, the initial perturbations are evaluated by calculating the pair of counter-interface-rotating vortex. It is confirmed the turbulent mixing by Rayleigh–Taylor instabilities is start from a quadratic growth, then move to a linear growth.

Statistical theory of inhomogeneous turbulence based on the cross-independence closure hypothesis

10716
Tue·14:15·5

Tomomasa Tatsumi
Kyoto University, Japan

Inhomogeneous turbulence in an incompressible viscous fluid is studied statistically using the cross-independence closure hypothesis which has been introduced by the author for closing the infinite set of the Lundgren–Monin equations for the multi-velocity distributions. The velocity field is decomposed into the mean velocity and the turbulent fluctuation around the mean. Then, closed equations are obtained for the mean velocity, the one- and two-point distributions of the fluctuation velocities using the closure hypothesis. In the case of zero mean velocity, a binormal one-point velocity distribution is obtained as a particular solution. A variety of free turbulent flows including wakes and jets can be expressed in terms of the linear combination of this type of distributions.

The influence of turbulence on a columnar vortex with axial flow

10745
Tue·14:20·5

Naoya Takahashi[†] and Takeshi Miyazaki
University of Electro-Communications, Japan[†]

The interaction between a columnar vortex and external turbulence is investigated numerically. A q-vortex (Lessen *et al.,* 1974) is immersed in an initially isotropic homogeneous turbulence field, which itself is produced numerically by a direct numerical simulation of decaying turbulence. We analyze the formation of vortical structures of the flow field using visualizing and statistical methods. In the marginally stable case with $q = -1.5$, small thin spiral structures are formed inside the vortex core. In the linearly unstable case, with $q = -0.45$, the linear unstable modes grow. Their growth rates agree with that of the linear stability analysis (Mayer and Powell 1992). After several turns of the vortex, the secondary instability causes the collapse of the columnar vortex and the sudden appearance of many fine scale vortices.

Numerical and experimental study of stability of isothermal and hot round jet

11124
Tue·14:25·5

Stanislaw Drobniak,[†] Andrzej Boguslawski and Artur Tyliszczaak
Czestochowa University of Technology, Poland[†]

The paper presents the results of experimental and numerical studies of isothermal and nonisothermal round jets at $Re = 5000$–20000 for the range of density ratio between the jet and ambient air equal $S = 0.5$–1.0. During the experiment a very low turbulence level ($Tu \leq 0.15\%$) was achieved and the shear layer thickness at the nozzle exit was varied in the range $40 < D/\theta < 200$. LES predictions of the jet in the range of flow conditions specified above were performed with high-order spectral and compact-difference code. During the numerical study the influence of governing parameters was verified and requirements for the mesh resolution and quality of subgrid models were also analyzed. It was confirmed by LES predictions that the strength of coherent vortices was much higher when the inlet turbulence level was sufficiently low. Moreover, it turned out that when inlet turbulence level was low the results were much more sensitive to the mesh resolution.

CICLoPE: a new high Reynolds number pipe flow facility for detailed turbulence measurements

11400
Tue·14:30·5

Jean-Daniel Rüedi,† Henrik Alfredsson, Hassan Nagib, Alessandro Talamelli and Peter Monkewitz
University of Bologna, Italy†

High Reynolds number turbulence is ubiquitous in a number of flow of practical interest and crucial to draw conclusions regarding the physics of turbulence. None of the turbulent wall bounded flow data set currently available provide simultaneously high enough Reynolds number, high resolutions and well converged statistics. The power required for detailed numerical simulation will not allow to obtain such data within decades to come, hence a new facility allowing to perform detailed turbulence measurements even at high Reynolds number is currently under construction at the Center for International Cooperation on Long Pipe Experiment, CICLoPE at the University of Bologna. The requirements to obtain a turbulent flow of practical interest are presented and used to define the specifications of a this new facility. The characteristics of several recent experiments are then compared to the present one to outline the complementarity of these various experiments.

Direct numerical simulation of turbulence in a fully-developed channel flow with permeable boundaries

11420
Tue·14:35·5

Satoshi Yokojima
Shizuoka University, Japan

Direct simulation of turbulent flow in a channel with perfectly permeable walls is performed to identify effect of wall imperviousness on turbulence in traditional plane channel. The results show that the permeable wall has a drag nearly two-order-of-magnitude higher than a solid wall. This indicates that wall imperviousness keeps near-wall quasi-laminar flow from being turbulent, which makes a substantial contribution to drag reduction in wall-bounded turbulent flows. It is also demonstrated that the permeable wall highly promotes momentum transport across the channel and sustain turbulence at such a low bulk Reynolds number where the flow with the traditional solid wall cannot be turbulent.

Concentration of active nonlinear energy transfer in rolling-up vortices

11738
Tue·14:40·5

Keisuke Araki† and Hideaki Miura
Okayama University of Science, Japan†

Nonlinear energy transfer process around rolling-up vortices that evolve from shear layers is studied numerically in terms of orthonormal divergence-free wavelets. The spatial scale and location information of wavelets is used to obtain scale-location-to-scale-location nonlinear energy transfer spectrum. Cone representation of the nonlinear transfer spectrum, whose vertex and base are located at wavelet mode modulus maxima, is developed to grasp visually the relation between coherent structures and nonlinear transfer process. Superposition of this cone representation on isosurfaces of enstrophy density shows remarkable correspondence. It is found that the region of active nonlinear energy transfer become narrower as the time goes.

Investigation of Smagorinsky model in large-eddy simulation of periodic turbulent shear flows

11699
Tue·14:45·5

Yihong Fang† and Dawei Guo
Tianjin University, China†

Large-eddy simulations of a space periodic turbulence flow have been used to examine in a detailed and quantitative manner the behaviour of Smagorinsky model with wall-matching function. Here, two LES computations have been carried out at grid resolutions $32 \times 32 \times 32$. The accuracy of present model was assessed by comparing results with those of DNS. The distribution Reynolds stress matches the results of DNS very well. The phase difference between Reynolds stress and rate of strain is also captured well. Our finding shows that the present model provided a reasonable good prediction and gave an encouraging result for the periodic turbulence shear flow.

Intensive turbulent convection

11839
Tue·15:00·E

Ilias Sibgatullin,† Semen Gertsenstein and Igor Palymsky
Moscow State University Lomonosov, Russia†

Within the frames of non-stationary Navier–Stokes equations direct numerical modeling of turbulent convection in a horizontal layer of a liquid heated from below is performed using the method of Bubnov and Galerkin. The basic attention is given to calculations at superhigh supercriticalities. For the reduction of computations for each step of integration the splitting method is used. It is preliminary shown that for small supercriticality the residual of the initial equations is small and the dependence of the residual on number of basic functions and supercriticality was shown. Good conformity of results after applying various schemes of numerical realization of Galerkin method was shown, in particular for stochastic processes at small supercriticality, arising with the formation of “strange” attractors close to Moebius’ band. Calculations in a wide range of supercriticality from 1 to 34000 are performed. Results of comparison of experiment and numerical modelling are shown.

Turbulent flow past a rectangular cylinder confined in channel

12147
Tue·15:05·E

Dong-Hyeog Yoon† and Kyung-Soo Yang
Inha University, South Korea†

Large-scale vortices shed from a cylindrical object as a vortex generator can be used to enhance heat transfer in a heat exchanger. As the first step towards proposing an effective method to control heat transfer in a heat exchanger using the vortices shed from a vortex generator, LES of turbulent flow past a rectangular cylinder confined in channel at $Re = 3,000$ (based on uniform inlet velocity and cylinder height) was performed with various values of cylinder aspect ratio to identify its effect on the flow characteristics. It turns out that the key flow statistics were significantly affected by the aspect ratio, especially in the near-wall region, indicating a possibility of utilizing the large-scale vortices shed from the cylinder to control heat transfer on the channel walls. The present LES results are in good agreement with the experimental results by Nakagawa *et al.* (1999).

Scale dependence of coarse-grained velocity gradient in turbulence

10532
Thu·09:15·5

Eberhard Bodenschatz,† Alain Pumir and Haitao Xu
MPI Goettingen, Germany†

We report here experimental results of coarse-grained velocity gradients from Lagrangian particle tracking measurements in fully developed turbulence. The coarse-grained velocity gradients are obtained from the tetrad model proposed by Chertkov *et al.* (Phys. Fluids, 11:2394, 1999). We investigated the scale dependence of the coarse-grained velocity gradient by varying the size of the tetrads. We observed more "flattening" in the inertial range while the coarse-grained velocity gradients approach Gaussian at large scales.

Multiscale geometrical analysis of vorticity and dissipation in homogeneous turbulence

11414
Thu·09:35·5

Dale Pullin,† Kiyosi Horiuti and Ivan Bermejo-Moreno
California Institute of Technology, USA†

A multi-scale methodology for the study of the non-local geometry of structures in turbulence is described. Starting from a 3D turbulence field, this consists of three main stages: extraction, characterization and classification. Structure extraction is done via the curvelet transform allowing a multi-scale decomposition, followed by isosurfacing the set of resultant 3D fields. Characterization is based on a probability density function of two surface differential-geometry properties, shape index and curvedness. Classification uses a feature space of parameters where clustering techniques search for groups of structures with common geometry. This methodology is applied to the vorticity and dissipation fields of a set of DNS with identical initial conditions and increasing grid resolutions 256^3, 512^3 and 1024^3. Results of this application, and its implications for the scale-dependent geometry of structures in turbulence, will be discussed.

Turbulence suppression by self-generated and imposed large-scale flows

11520
Thu·09:55·5

Hua Xia,† Michael Shats, David Byrne and Horst Punzmann
The Australian National Univeristy, Australia†

How a large-scale flow influences turbulence is a question of both fundamental and practical importance. We report the first experimental evidence of the suppression of two-dimensional turbulence by large-scale flows. The shear decorrelation of the turbulent eddies and the sweeping of the forcing scale vortices are responsible for the turbulence suppression. The shear flattens the spectrum (larger scales are affected more), while the sweeping reduces the energy flux from the (small) injection scale. Two cases are considered when the large-scale flow is imposed externally, or it is generated in the process of spectral condensation of turbulence.

Deterministic wall turbulence and its applications

10626
Thu·10:15·5

Yury Kachanov,† Vladimir Borodulin and Aleksej Roschektayev
Russian Academy of Sciences, Russia†

The notion of 'deterministic turbulence' is introduced and substantiated. The experimental results on realization of this turbulence in a boundary-layer flow are presented. Possible applications of the deterministic turbulence approach are discussed. An example of utilizing of this approach for investigation of physical mechanism of viscous drag reduction by LEBU-devices is given. It is shown that this approach represents a very efficient tool for turbulence research. This work is supported by the Russian Foundation for Basic Research (Grant N 08-01-91951).

A bound for turbulent pair dispersion

11178
Thu·11:00·5

Michael Borgas
CSIRO, Australia

A new approximation between two fundamental mixing properties in turbulence defines a lower bound on backwards pair dispersion. This is consistent with stochastic models of pair dispersion and helps constrain a highly uncertain natural phenomenon which is important for mixing in practical situations like dispersion of pollution in the atmosphere. The Lagrangian particle formulation and inertial range scaling and dispersion are used to link the properties and derive the key results. Integral inequalities define specific quantitative constraints and deal with arbitrary functional scaling forms. This work captures some interesting history of turbulence theory, yet has impact on the most recent examinations of backwards pair dispersion and the most modern measurements of Lagrangian properties. This recent knowledge is only now defining the quantitative properties for practical mixing.

Experimental measurement of acceleration correlations in turbulent flows of dilute polymer solutions

11402
Thu·11:20·5

Haitao Xu† and Eberhard Bodenschatz
Max Planck Institute for Dynamics and Self-Organization, Germany†

We measured fluid accelerations in the bulk of a turbulent flow of dilute polymer solutions by optically following neutrally-buoyant, passive tracer particles in the flow. The polymer additives suppressed the acceleration variance but had little effects on the shape of the acceleration probability density function, consistent with previous experimental results. We also observed long-range correlations of acceleration in dilute polymer solutions. The longitudinal and the transverse acceleration correlations satisfy the relation for homogeneous and isotropic turbulence in Newtonian fluids, which sets a constraint for the polymer stress tensor in the bulk turbulence.

Physical mechanism of the energy cascade in homogeneous turbulence

11889
Thu·11:40·5

Susumu Goto
Kyoto University, Japan

Energy cascades from larger to smaller scales in turbulent flow. Through this process, the information of large-scale external conditions is forgotten, and the well-known small-scale universality of turbulence is achieved. The energy cascading process in the wavenumber space has been investigated by many authors, and it has been widely recognised that energy indeed cascades locally from smaller to larger wavenumber Fourier modes. However, little is understood about its physical mechanism. Therefore, in this paper, we investigate the physical-space energy cascade by detailed analyses of direct numerical simulation data of homogeneous isotropic turbulence. For this purpose, we introduce a local energy and its transfer rate of turbulent velocity field as a function of scale, space and time. Then, it is shown that the energy cascade can be caused by smaller-scale vortex creations in larger-scale straining regions between anti-parallel pairs of larger-scale tubular vortices.

On local cascade structures of turbulence **11963** Thu·12:00·5

Zhen-Su She,† Jun Chen and Yu-Hui Cao
Peking University, China†

We propose a new notion of turbulent structures based on statistical characterization of cascade. A local cascade (LC) structure is designed to analyze a scalar 2D fluctuation field embedded in a 3D space, such as any velocity component variation on a plane. Application of the LC structure analysis in a turbulent channel flow is presented. On each plane, the whole field is decomposed into five classes of LC structures, each of which corresponds to one scenario of breaking a local 2D uniform pattern into further variations when going down to smaller scale. Then, the analysis of their spatial distributions rediscovers familiar geometrical features of near-wall streaks, and their associated kinematic study captures fast phase-convection of structures very close to the wall. Most interestingly, the analysis yields a theoretical calculation of local Leonard stress, which are in good agreement with the DNS evaluation. This opens the possibility for structure-based turbulence modelling.

A study of subgrid models in lattice Boltzmann-based large eddy simulation **11443** Thu·12:20·5

Yu-Hong Dong,† Simon Marie and Pierre Sagaut
Shanghai University, China†

A variation Smagorinsky model and the classical Smagorinsky model are applied to the large eddy simulation of decaying homogenous isotropic turbulence based on the lattice Boltzmann method which is implemented using the D3Q19 lattice model. The LES-LBM results are compared with the direct numerical simulation data as well as experimental data. The time evolution of the kinetic energy and the decay exponents of the dissipation rate, the velocity derivative skewness, instantaneous energy spectra are analyzed. The dependency of behavior of the model coefficients on the ratio of grid width and the Kolmogorov scale is examined numerically. The results demonstrate that the LES-LBM in conjunction with the IR consistent Smagorinsky model can be used to simulate turbulence more satisfactorily than the standard Smagorinsky model.

Scaling regimes of the 2D Navier–Stokes equation with self-similar stirring **11915** Fri·09:15·5

Paolo Muratore-Ginanneschi,† Andrea Mazzino and Stefano Musacchio
University of Helsinki, Finland†

We numerically inquire the scaling properties of the 2D Navier–Stokes equation sustained by a forcing field with self-similar Gaussian statistics and power spectrum of degree $3-2\,\varepsilon$. We contrast our results with the conflicting predictions of Kraichnan's theory and of renormalization group (RG) analysis. We give clear evidence that for all ε Kraichnan's theory is consistent with our numerics. Our results pose a serious challenge for the application of RG methods in turbulence.

Discussion on the rapid pressure–strain correlation in the rapid distortion limit

10598
Fri·09:35·5

Song Fu† and Siyuan Huang
Tsinghua University, China†

The rapid part of pressure-strain correlation is one of the key elements in the DRSM. However, the current pressure-strain correlation models (the M-tensor for rapid pressure-strain term is expandable in the Reynolds-stress anisotropy tensor alone) still exhibits some apparent deficiencies when subjected to flows in RDT limit. For pure rapid rotation of an initial anisotropic state, RDT shows the anisotropy will exhibit the behavior of damped oscillations, but the current models will give undamped oscillations; for initially isotropic turbulence, RDT shows two distinct paths in the anisotropy-invariant map for plane strain and shear flows, but the current models would deliver the identical path. Lee *et al.* shows RDT may give an accurate description of the turbulence at realistic strain rates in a study of plane shear flows. Present work presents a possible candidate to overcome these deficiencies by introducing the strain and rotation rate tensors S and Ω to the expansion of M-tensor.

Gradient statistics in the shearless turbulent mixing

11573
Fri·09:55·5

Daniela Tordella† and Michele Iovieno
Politecnico di Torino, Italy†

The velocity derivative statistics in the simplest inhomogeneous turbulent flow, the shearless turbulent mixing, are analyzed using data from direct numerical simulations at a Taylor Reynolds number of 45. We show that there is a significant skewness and kurtosis of both the longitudinal and transversal derivative of the velocity component in the direction of the mixing. The small-scale anisotropy of the third order moments increases with the turbulent energy gradient which produces the mixing and is of the same order of that observed in homogeneous sheared turbulence at the same Reynolds number.

Large eddy simulations of a self-similar mixing layer using the stretched-vortex subgrid model

10449
Fri·10:15·5

Trent Mattner
The University of Adelaide, Australia

Large eddy simulation of a temporal mixing layer using the stretched-vortex model produces a flow that is self-similar during a limited time interval. During that time, the growth rate, mean velocity and Reynolds stress are in accord with experimental results. The scalar probability density function, however, has a marching character and the fluid near the centre of the layer is almost all mixed to some degree, even at large Schmidt number.

FM20 :: Waves

Chairs: Frederic Dias (France) and Kendall Melville (USA)

Mon	14:00–16:00	Hall A	Lectures
Mon	16:25–17:45	Hall A	Lectures
Tue	15:00–15:15	Hall C	Seminars
Tue	16:00–17:40	Hall A	Lectures
Wed	10:40–13:00	Hall A	Lectures
Thu	09:15–10:35	Hall A	Lectures

A practical forecast model for atmospheric internal waves produced by a mountain

10504
Mon·14:00·A

James Rottman,[†] Dave Broutman and Stephen Eckermann
SAIC Naval Hydrodynamics, USA[†]

A fast operational forecast model is developed for the internal wave field generated by realistic atmospheric flows over three-dimensional mountains. The model is based on the assumption that sufficiently far above the mountain the internal waves are linear and a Fourier-ray approximation is valid. This model can compute rapidly the complicated refraction and reflection of the waves caused by height-dependent stratification and winds that are characteristic of a realistic atmosphere. The approximation breaks down at turning points, altitudes where nearby rays cross, leading to predictions of infinite wave amplitudes. In realistic atmospheres it is likely that there are multiple turning points for many of the waves and the solutions at these locations are corrected in a practical way to get reasonable predictions of the wave field. The approximate solutions for the wave field are compared with mesoscale model simulations for idealized and realistic atmospheric mountain flows.

Internal solitary waves of very large amplitude subject to shear-instability

10576
Mon·14:20·A

John Grue
University of Oslo, Norway

Twenty-four experiments on the onset of shear-induced breaking of internal solitary waves of very large amplitude are investigated in laboratory wave tanks with support from fully nonlinear computations. The waves move along a linearly stratified pycnocline sandwiched between two layers of homogeneous density, one thin (the upper) and one thick (the lower). All experiments with minimum Richardson number Ri_{min} less than 1/4 fall within the range $Ri_{min} = -0.23L/\lambda + 0.298 \pm 0.016$, where L denotes the horizontal length of a pocket with Richardson number less than 1/4, and λ the wave width, the latter defined at the level of half maximum excursion of the pycnocline. Shear-induced breaking begins at wave maximum and evelops in the tail of the wave when L/λ exceeds 0.86. The minimum Richardson number is in the range between 0.09 and 0.11, for $L/\lambda = 0.86$, at threshold. Measured and computed Kelvin–Helmholtz billows have a wavelength of 7.9 times the pycnocline thickness.

Nonlinear wave excitation of capillary waves in the presence of hydrocarbon films

11066
Mon·14:40·A

Horst Punzmann† and Michael Shats
The Australian National University, Australia†

This paper presents experimental results of the effect of hydrocarbon films on the nonlinear excitation of capillary waves. Experiments have been conducted in a wave tank using a microwave scattering technique capable of measuring the wave dispersion relation. Results indicate that the threshold for sub-harmonic nonlinear wave excitation is affected by viscous damping of the hydrocarbon film. At low damping, the $f/2$ sub-harmonic precedes the onset of a low-frequent sideband in the gravity-capillary wave range as the forcing amplitude is increased.

Open channel flow past a curved sluice gate

10661
Mon·15:00·A

Ben Binder,† Jean-Marc Vanden-Broeck and Frederic Dias
University of Melbourne, Australia†

Free-surface flows past flat or curved plates in an open channel are classical problems in fluid dynamics. Solutions can be viewed as approximations for flow past surfboards, hydrofoils, and sluice gates. We present new results for wave-less flow past a curved sluice gate, and compare them with the already known results for flat sluice gates. The number of independent parameters for a particular flow configuration is determined through a weakly non-linear analysis of the problem, and non-linear solutions are computed using boundary integral equation methods.

Wave-coherent tangential stress due to smaller scale breaking

11249
Mon·15:20·A

William Peirson† and Andrew Garcia
Water Research Laboratory, Australia†

The growth of water waves by the wave-coherent tangential stress generated by shorter breaking waves has been carefully examined during recent laboratory experiments. The strongest normalised growth rates are observed at low wave steepnesses, implying a significant wave-coherent tangential stress contribution. Normalised growth rates decline appreciably and systematically with increasing wave steepness, providing a plausible explanation of previously observed scatter in measurements which did not consider the potential role of wave steepness. Quantitative agreement is found between theoretical predictions of long wave modulation of short waves and saturation of the short wave field by breaking. Measured normalised wind-induced wave growth rates are consistent with numerical predictions of wave drag augmented by significant but plausible levels of wave-coherent tangential stress.

Surface gravity waves in Lagrangian description of motion

11868
Mon·15:40·A

Didier Clamond
University of Nice, France

This presentation concerns the mathematical formulation of steady surface gravity wave in Lagrangian description of motion. A general mathematical formulation of steady surface gravity wave in Lagrangian description of motion is given for incompressible fluids. A Lagrangian Stokes-like expansion is subsequently introduced and illustrated for irrotational surface waves in deep water. This approximation is free of secular terms, unlike the ones obtained at higher-orders from Stokes' original perturbation scheme.

Nonlinear three-dimensional interfacial flows

10109
Mon·16:25·A

Emilian Parau,† Jean-Marc Vanden-Broeck and Mark Cooker
University of East Anglia, UK†

A configuration consisting of two superposed fluids bounded above by a free-surface is considered. Steady three-dimensional potential solutions generated by a moving pressure distribution are computed. The pressure can be applied either on the interface or on the free-surface. Solutions of the fully nonlinear equations are calculated by boundary-integral equation methods. Fully-localized gravity-capillary interfacial solitary waves are also computed, when the free surface is replaced by a rigid lid. These wave have damped oscillations in the direction of propagation, and decay monotonically in the transverse direction. Further results will be presented for related problems, e.g. waves on fluid layers in the presence of electric fields. Time-dependent flows will be discussed.

Inertial estimates of surface wave dissipation due to breaking

10534
Mon·16:45·A

Kendall Melville,† Luc Lenain and David Drazen
Scripps Institution of Oceanography, USA†

Surface wave breaking is important for understanding the coupling between the wave field and the upper ocean. Wave dissipation per unit length of breaking crest, ϵ_l, is proportional to $\rho_w g c^5$, where ρ_w is the density of water, g is gravity and c is the phase speed of the wave. Early estimates of the proportionality factor, or "breaking parameter" b, were poorly constrained. Here we describe inertial scaling of dissipation by plunging breakers, which give $b = \beta(hk)^{5/2}$, where hk is a local slope parameter, and $\beta = O(1)$. This prediction is tested with measurements of breaking by dispersive focusing in a wave channel. Good agreement is found within the scatter of the data. If a linear measure of the maximum slope of the wave packet, S, is used then $b \propto S^{2.77}$ gives better agreement with data. We discuss the significance of these results in the context of recent measurements and modelling of breaking.

Spatial and temporal evolution of wave groups: experiments versus simulations

10744
Mon·17:05·A

Lev Shemer,† Alexey Slunyaev and Boris Dorfman
Tel-Aviv University, Israel†

Evolution of a narrow-spectrum unidirectional nonlinear wave group in a deep laboratory wave tank is studied both experimentally and numerically. Contrary to measurements by wave gauges distributed along the experimental facility that present the evolution of the wave group in space, digital processing of sequences of the video images of the wave field was performed to study evolution of the whole wave field in time as well. The experimental results on the spatial evolution of the wave group are compared with simulations based on the Modified Nonlinear Schrödinger equation due to Dysthe. The temporal evolution is studied using two different implementations of the Dysthe equation, as well as the strongly nonlinear code of Dommermuth & Yue and the fully nonlinear code of Dyachenko & Zakharov. All models applied yield results that are in a good agreement with the experiment. Some differences between the various models require further attention.

Short-crested gravity waves of large amplitude in deep water

10870
Mon·17:25·A

Makoto Okamura
Kyushu University, Japan

We calculate short-crested gravity waves using the Galerkin method and the collocation method, and then compare their results. Next, nearly limiting short-crested waves are calculated in the case $\theta = 45°$ and $\theta = 85°$. We have found that (i) the Galerkin method is more useful than the collocation method to obtain very-large-amplitude waves and (ii) the enclosed crest angle of the limiting wave is $90°$ in the case $\theta = 45°$, while it is very close to $120°$ in the case $\theta = 85°$. These enclosed crest angles correspond to the standing wave's and the two-dimensional progressive wave's, respectively.

Combined approach to the dynamics modelling of spatially nonlinear waves in shallow layers of viscous liquids

10790
Tue·15:00·C

Georgy Khabakhpashev† and Dmitry Arkhipov
Institute of Thermophysics SB RAS, Russia†

This paper deals with the novel approach to the evolution description of nonlinear three-dimensional moderately long perturbations of the homogeneous liquid free surface or of the two-layered fluid interface. There are assumed that liquid is incompressible, its stationary flow is absent, the disturbance amplitudes are small but finite, characteristic horizontal lengths of waves and of the bottom topography are larger and the thickness of unsteady viscous boundary layer is smaller than the fluid depth. The obtained model consists of one basic evolution equation for spatial perturbations and auxiliary differential equations for a determination of the liquid horizontal velocity vector averaged over the layer depth which is contained in the main equation only in the terms of the second order of smallness. The suggested approach is applicable for waves running simultaneously in different directions. Some solutions of this system of equations were found numerically.

Analyses on the flapping frequency of turbulent jets in a narrow channel

11905
Tue·15:05·C

Jianhong Sun† and Chin-Tsau Hsu
Nanjing University of Aeronautics and Astronautics, China†

The flapping motion of a turbulent plane jet is a lateral oscillation of the jet, which was theoretically and experimentally regarded by Goldschmidt and Bradshaw, and de Gortari and Goldschmidt, as the unstable motion due to the coherent turbulent structure. And it is evident from the research of Hsu *et al.* that the self-excited jet flapping motion is attributed to the jet instability rather than the coherent turbulent structure. Based on investigations in decades, the wall effect on flapping frequency of turbulent jets in a narrow channel was studied in this paper. The LDV measurement data showed that the flapping frequency in narrow channel is same as that of flapping motion of turbulent plane jets when the jet exit velocity is larger than the critical value. But the frequency keeps a constant in some regions of water depth, defined as frequency lock-in phenomenon. The theoretical analyses show that the reason of frequency lock-in is from the effect of reflection waves.

Dynamic wave impact simulation using an innovative particle-cluster scheme

10211
Tue·15:10·C

André Baeten
LFK-Lenkflugkoerpersysteme GmbH, Germany

In this Paper, the wave impact on a solid submitted to forced osciIlations is highlighted. This kind of wave impact is typical for offshore applications like ship foredeck loading where the ship undergoes low-frequency, but high amplitude oscillations. The simulation has been done using an innovative three-dimensional particle-cluster scheme that is able to simulate complex liquid dynamics. A large number of microscopic liquid particles (molecules, ions) are supposed to be concentrated in particle-clusters of macroscopic dimensions. These clusters interact via a Lennard–Jones potential. The potential parameters have been transformed into macroscopic domain using fundamental mechanical, thermodynamical arid chemical relations. The wave impact has been simulated time-accurately in six degrees-of-freedom. The simulation results have been successfully validated against experiments and CFD simulations carried out at Groningen University, The Netherlands.

Nonlinear surface water waves over a random bottom

11047
Tue·16:00·A

Walter Craig† and Catherine Sulem
McMaster University, Canada†

In the theory of ocean wave propagation it is a common situation to have partial but not complete bathymetric information. The basic contours of the bottom on a large lengthscale are known, while the detailed topography on a short lengthscale is modeled by a stationary random process. In this setting we show that nonlinear solitary water wave solutions exist, and are effective means to rapidly propagate energy and momentum over long distances. However the cumulative effect of the bottom variations results in a random motion of the phase, a white noise component to the modulation of the amplitude, and a random scattered component along backwards characteristics. The analysis of this phenomenon involves averaged Hamiltonian perturbation theory, homogenization and scale separation, and the degree to which the problem fails to homogenize fully is quantified by Donsker's invariance principle.

Impact of a heavy vertical jet on a horizontal wall

11146
Tue·16:20·A

Paul Christodoulides† and Frederic Dias
Cyprus University of Technology, Cyprus†

Steady two-dimensional jets of an inviscid and incompressible fluid emerging from a vertical nozzle hitting a finite horizontal plate and falling under gravity are calculated numerically by series truncation. Solutions are determined for various values of the Froude number leading to three different families of configurations. Imposing a stagnation point yields solutions that do not seem to depend on the horizontal coordinate, while it is shown that there are limiting values for the vertical coordinate of the stagnation point. The study is extended to the case of a stream emerging from a nozzle and splitting into two non-symmetric jets, without hitting the horizontal plate, as well as for cases where the nozzle is inclined at an angle β. Finally, comparisons between solutions obtained here as well as with solutions of previous studies are also presented.

Nonlinear surface waves in a square liquid tank under obliquely horizontal excitation

11736
Tue·16:40·A

Takashi Ikeda† and Raouf Ibrahim
Shimane University, Japan†

Nonlinear responses of surface waves in a square tank partially-filled with liquid subjected to horizontal excitation along an oblique angle are investigated. When the direction of the excitation is close to the diagonal line of a tank cross section, two modes of sloshing are significantly coupled with each other due to the nonlinear liquid inertia. In the theoretical analysis, modal equations for the six different modes of sloshing are derived and effect of linear damping is then included. Next, the expressions of the frequency response curves are determined using van der Pol's method. In the numerical results, the influence of the excitation direction is primarily examined. When the excitation frequency is close to the natural frequency of the two degenerated sloshing modes, Hopf bifurcation may occur. If Hopf bifurcation appears, amplitude modulated motions (including a chaotic vibration) may also occur. These theoretical results were also observed in experiments.

Effect of surface stress on the propagation of solitary water waves

11768
Tue·17:00·A

Paul Hammerton† and Andrew Bassom
University of East Anglia, UK†

An equation is derived governing the weakly nonlinear propagation of long wavelength disturbances on the surface of a fluid layer if an arbitrary stress is applied at the surface. If the stress only acts in the normal direction, as is the case for constant surface tension or the effect of an electric field on a perfect conductor, the large Reynolds number limit gives a governing equation in the form of a modified KdV equation with a dissipation terms due to the boundary layer at the base of the fluid. For the case of a normal electric field and a perfectly conducting fluid, inviscid theory leads to a modification of the KdV–Benjamin–Ono equation. However if tangential stress arises at the surface, for example due to variable surface tension, then the effect of the boundary layer at the surface must be considered. The parameter range when this affects the propagation of solitary waves is determined and numerical examples presented.

Giant solitons on deep water and freak waves

11863
Tue·17:20·A

Vladimir Zakharov† and Alexander Dyachenko
University of Arizona, USA†

We show numericaly that the strong localized perturbation of free fluid surface could propagate on the surface of deep fluid. These perturbations are “breathers”, in a sense that the motion of surface is a periodic function on time in a certain moving framework. Breathers of small steepness (less then $ka = 0.07$) are known as solitonic solutions of the Nonlinear Shrödinger Equation (NLSE). Our new result is the following: the breathers exist up to very high steepness (at least to $ka = 0.7$). These steep giant breathers can be identified with freak waves. Our numerical experiments show that the giant breather inevitably appear as a result of development of the modulational instability. The most plausible explanation of the giant breather stability is integrability of the Euler equation describing a potential flow of deep ideal fluid with free surface.

Three-dimensional gravity capillary free surface flows

11786
Wed·10:40·A

Jean-Marc Vanden-Broeck,† Emilian Parau and Mark Cooker
University College London, UK†

Three dimensional free surface potential flows are considered. The problem is solved numerically by using an integro-differential equation formulation. Accurate nonlinear solutions are calculated for the free surface flow generated by a disturbance moving at a constant velocity c. It is shown that for small values of c, there are solutions which are perturbations of three dimensional solitary waves. These solitary waves are generalisation to three dimensions of known two dimensional solitary waves. For larger values of c, there are wave patterns on the free surface. Solutions are then calculated by introducing a small amount of dissipation in the dynamic boundary condition in order to satisfy the radiation condition. We conclude the talk by discussing time dependent three dimensional free surface flows.

Adaptive direct numerical simulation of steep water waves

10397
Wed·11:00·A

Stéphane Popinet
National Institute of Water and Atmospheric research, New Zealand

Air entrainment and spray formation by spilling or breaking waves are important processes for the quantification of ocean/atmosphere fluxes of soluble gases, heat and momentum. While two-phase interfacial flow numerical techniques can be applicable to the study of water waves, they are often limited by an inaccurate representation of surface tension and prohibitive computational cost, particularly in three dimensions. I will show that both of these limitations can be overcome using novel surface tension representation schemes and spatially-adaptive discretisation techniques. These methods give accurate solutions for weakly non-linear capillary/gravity waves while allowing efficient three-dimensional simulations of air entrainment and droplet formation for spilling and breaking waves. They can also be coupled to the solution of advection/diffusion equations for scalar transport in order to carry out direct studies of the coupling between wave dynamics and scalar fluxes.

On the inclusion of arbitrary topography and bathymetry in the nonlinear shallow-water equations

11451
Wed·11:20·A

Raphael Poncet† and Frederic Dias
École Normale Supérieure de Cachan, France†

The nonlinear shallow water equations are used in a lot of applications. The application of interest here is the evolution of the wave field over large coastal areas (many square kilometres). Several problems must be dealt with: the translation of input data obtained from phase-averaged into a phase-resolving code, the handling of arbitrary bathymetry and topography, the handling of runup and rundown, the precise definition of mean sea level. The nonlinear shallow water equations are solved with a second-order finite volume solver on unstructured meshes. Data acquisition and mesh generation are automated with custom scripts using the `Python` language. Preliminary results will be presented.

Space-time measurements of breaking wave kinematics and void fraction in the surf zone

11622
Wed·11:40·A

Olivier Kimmoun† and Hubert Branger
Aix-Marseille Université and Ecole Centrale Marseille, France†

Particle Image Velocimetry (PIV) measurements were performed in a wave tank under regular water waves propagating and breaking on a 1/15 sloping beach. To obtain more accurate measurements, the domain from the initiation of the breaking to the swash zone is splited in fourteen overlapping windows. The full field is reconstructed at each time step by gathering the fourteen synchronized PIV fields. We measured then the complete space-time evolution of velocity field over the whole surf zone. From these data the ensemble-period-average and phase-average components of the flow with their associated fluctuating parts were computed. Moreover using the light intensity of the PIV images and velocity measurements, we estimated the void fraction in each point of the surf zone and at each time step.

Numerical study of breaking waves of different intensities

11809
Wed·12:00·A

Alessandro Iafrati
INSEAN—Italian Ship Model Basin, Italy

The flow generated by the breaking of free surface waves of growing steepness is investigated numerically. The study is done through a two-fluids Navier–Stokes solver coupled with a Level-Set technique for the interface capturing which allows the analysis of the flow in both air and water. Depending on the initial steepness the wave train remains regular or evolves toward breaking, either of the spilling or plunging type. Simulations are done for a two-dimensional flow, incompressible fluids. We assume a periodic wave train and study its evolution in time in a computational domain with periodic boundary conditions at the two sides. The initial free surface profile is a third order accurate Stokes wave and the steepness is varied from 0.2 to 0.65. The analysis is focussed on bubble entrainment, vorticity production in water and air and energy dissipation.

The frequency and wavevector spectra of gravity wave turbulence in the laboratory flume

11375
Wed·12:20·A

Sergei Lukaschuk,† Petr Denissenko and Sergey Nazarenko
The University of Hull, UK†

In order to understand the mechanisms of wave turbulence we study experimentally k- and ω-energy spectra of surface gravity waves generated in a rectangular flume with dimensions $6 \times 12 \times 1.5$ m. The waves were excited by a quasi-periodic force. The surface elevation was measured simultaneously as a function of time at two fixed points using capacitance probes, as a function of x-coordinate along a surface line at fixed times using the laser sheet technique. The results are presented in terms of the k- and ω-energy spectra. We found that for a wide range of excitation amplitudes the energy spectra have a power-law scaling, $E_\omega \sim \omega^a$ and $E_k \sim k^b$. The exponents a and b are not universal: they change from -6 to about -4 and from about -4.2 to -3 for ω- and k-spectra correspondingly when the wave intensity increases.

Airflow separation above wind waves

11808
Wed·12:40·A

Fabrice Veron,† Marc Buckley and James Mueller
University of Delaware, USA†

The influence of waves and in particular the effects of airflow separation is arguably the largest uncertainty in determining precise air-sea momentum fluxes for a variety of conditions. We present laboratory measurements of the velocity in the airflow above wind-waves. These data, obtained using PIV techniques, yielded the velocity within the viscous sublayer above the wavy surface. Concurrently, we estimate the surface viscous tangential stress in the airflow. The separation of the viscous sublayer past the crest of the wind-waves leads to the transport of vorticity away from the surface and the generation of significant mixing. The separation also causes dramatic along-wave variability of the surface stress and velocity. These results hold for wind speeds that would normally be considered benign. Furthermore, the statistics of separation events correlate with surface wave slope parameters. We compare the results with available theoretical predictions.

On the self-similarity of short-wavelength incipient spilling breakers

11082
Thu·09:15·A

James Diorio,† James Duncan and Xinan Liu
University of Maryland, USA†

In this work, the profiles of incipient spilling breaking waves were studied experimentally in clean water. Waves were generated using either a mechanical wave-maker or wind. The crest profiles were measured with a laser-induced fluorescence technique. In the cases considered herein, the breaking process is initiated with the formation of a bulge on the forward face of the wave and capillary waves upstream of the leading edge ("toe") of the bulge. It was found that when the profiles are aligned at the toe and rotated such that there is a common surface slope upstream of the toe, the crest profiles are self-similar, and a simple scaling causes the profiles to collapse, independent of the method used to generate the wave. Furthermore, several geometrical parameters used to describe the crest shape are found to depend on a measure of the local surface slope at the toe point. These trends remain consistent over the entire range of wavelengths and breaker conditions studied.

Measurements of growth rates of wind-generated water waves

11058
Thu·09:35·A

Dan Liberzon† and Lev Shemer
Tel Aviv University, Israel†

Experimental investigation of water wave excitation by wind is carried out in a small scale wind-wave flume. Extensive set of data is accumulated with the purpose to enable quantitative comparison of experiments with predictions of wind-wave generation models. A variety of measurement techniques is applied, such as an array of capacitance wave gauges, hot-wire anemometer and water surface tracers in combination with particle tracking analysis. The measured parameters include wind velocity and turbulence level profiles, instantaneous wave heights, wave spectra and phase velocities, as well as water surface drift velocities. Evolution of the wave field along the flume and spatial growth rates for waves in different frequency bands are determined for a wide range of wind velocities. Waves' phase velocities were found to be affected by the wind driven water surface drift currents.

Drag on a ship and Michell's integral

11452
Thu·09:55·A

Ernest Tuck[†] and Leo Lazauskas
The University of Adelaide, Australia[†]

This year marks the 110th anniversary of Michell's landmark paper on the wave resistance of thin ships. We show that when combined with the standard ITTC technique for estimation of the skin friction, Michell's method is still competitive with a modern CFD code for the total drag on a Wigley hull with a length/beam ratio of 8, at a much reduced cost.

Visco potential free-surface flows

10872
Thu·10:15·A

Denys Dutykh
Ecole Normale Superieure de Cachan, France

In a recent study D. Dutykh and F. Dias (2007) presented a novel formulation for visco potential free surface flows. The governing equations contain local and nonlocal dissipative terms. The local dissipation terms come from molecular viscosity. On the other hand, the nonlocal dissipative term in the kinematic bottom condition represents a correction due to the presence of a bottom boundary layer. Corresponding novel long wave equations (Boussinesq and Korteweg-de Vries type) are derived. The properties of the dispersion relations of the proposed models are analysed. The effect of the nonlocal term on solitary and linear progressive waves attenuation is investigated.

SM01 :: Computational solid mechanics

Chairs: Jacob Fish (USA) and Wanxie Zhong (China)

Mon	14:00–16:00	Room 1	Lectures
Tue	14:00–14:55	Hall B	Seminars
Thu	11:00–13:00	Room 2	Lectures
Fri	11:00–12:20	Room 2	Lectures

Multiscale finite element simulation for crack propagation in heterogeneous media with microstructures

10130
Mon·14:00·1

Seyoung Im,† Jae Lim and Dongwoo Sohn
Korean Advanced Institute of Science and Technology, South Korea†

A noble multiscale FE scheme is proposed for simulation of crack propagation in heterogeneous media with microstructures. The fine scale mesh is constructed to model the presence of microstructures around the near-tip field region, while the coarse-scale mesh is introduced to model the far-field region, wherein the effect of the microstructures is averaged through the homogenization theory to yield the average macroscopic constitutive relationship. Then the so-called variable-node elements are employed to connect the fine-scale zone in a seamless way to the coarse-scale zone. Some numerical examples show that the scheme leads to an effective tool for multiscale simulation of crack propagation in consideration of the microstructures in a heterogeneous body.

3D gradient elastic crack analysis by the BEM

10208
Mon·14:20·1

Dimitri Beskos,† Stephanos Tsinopoulos, Demosthenes Polyzos and Gerasimos Karlis
University of Patras, Greece†

A Boundary Element Method (BEM) for solving the three dimensional (3D) mode I fracture mechanics problem in gradient elastic materials is presented. The gradient elastic theory used can be considered as the simplest case of the general gradient elastic theory proposed by Mindlin. A new 3D special, variable order of singularity discontinuous element is described for the singular fields treatment around the crack tip and the accurate evaluation of the Mode-I stress intensity factor (SIF). The utilized displacement-based BEM employs the 3D gradient elastic fundamental solution recently derived by the authors and this restricts the problem discretization only to the boundary surfaces. The crack profiles and the corresponding SIFs for different values of the gradient elastic coefficient (internal length scale parameter) are obtained and compared to the corresponding classical ones in order to assess the effect of the microstructure on the stress and deformation fields around the crack tip.

Nonconforming BETI/FETI method for time domain elastodynamics

10257
Mon·14:40·1

Martin Schanz† and Thomas Rüberg
Graz University of Technology, Austria†

A methodology for the combination of boundary and finite element discretizations for the numerical analysis of time-dependent problems is presented. The main idea is to construct a discretised version of the Steklov-Poincaré operator for the dynamic problem. The interface conditions arising from the partitioning of the problem are incorporated in a weak form by means of Lagrange multiplier fields and, therefore, allow for nonconform interface discretizations. The resulting system matrices have the same saddle point structure as in the FETI/BETI method. Possible applications of the proposed method are the dynamic analysis of soil-structure interaction and similar wave propagation phenomena in unbounded media. Exemplary results for a coupled bar and a foundation on a half space are presented. The first is used to validate the algorithm, whereas the latter shows the applicability in soil-structure interaction.

Two-field and two-scale computational homogenization for coupled thermo-mechanical problems

10562
Mon·15:00·1

Marc Geers,† Izzet Ozdemir and Marcel Brekelmans
Eindhoven University of Technology, Netherlands†

This paper presents a two-scale computational homogenization framework that handles two coupled fields (thermal and mechanical) in an operator split manner. The key principles of a two-field computational homogenization scheme are shortly discussed. The homogenization of each of the fields is based on a first-order computational homogenization scheme, which is particularly commented for the thermal part. The interaction between the mechanical and thermal fields through the temperature induced stresses, temperature dependent material properties and the influence of geometrical changes (large displacements and internal discontinuities) on the thermal field leads to a coupled problem at both micro and macro levels. An illustrative example is presented, where an incrementally coupled implementation is used to solve the interaction between microstructural fields and macroscopic fields upon thermo-shock loading.

A generalized cosserat point element for isotropic nonlinear elastic materials including irregular 3D brick and thin structures

10732
Mon·15:20·1

Miles Rubin† and Mahmood Jabareen
Technion - Israel Institute of Technology, Israel†

A generalized form for the strain energy of inhomogeneous deformations is developed for a 3-D brick Cosserat point element (CPE) which includes full coupling of bending and torsional modes of deformation. The constitutive coefficients, which depend on the reference geometry of the element, are determined by solving eighteen bending problems and six torsion problems on special elements that are parallelepipeds with two right angles. The resulting constitutive coefficients ensure that the strain energy for inhomogeneous deformations remains a positive definite function of the inhomogeneous strain measures for all reference element shapes. A number of example problems are considered which show that the generalized CPE produces results as accurate as enhanced strain and incompatible elements for thin structures and is free of hourglass instabilities typically predicted by these enhanced elements in regions experiencing combined high compression with bending.

Model verification in dynamics through strict upper error bounds

11098
Mon·15:40·1

Pierre Ladeveze† and Julien Waeytens
École Normale Supérieure de Cachan, France†

Modeling and simulation are central to any mechanical engineering activity. There are numerous sources of error: modeling, space-time discretization, iteration stopping. One of the key topics is the quality assessment of calculated outputs of interest obtained, for example, by finite element analysis. The objective goes beyond that of earlier error estimators, which provided only global information. Since most of the available error estimators are nonconservative, the derivation of efficient and guaranteed upper error bounds for calculated outputs of interest is currently a challenge. The central questions discussed here are how to get efficient and guaranteed error bounds and how to calculate them in Dynamics. A general and recent answer for small displacement problems is introduced. Usual convexity properties are assumed through the standard thermodynamic framework with internal variables. This involves nonclassical concepts such as the dissipation error or the mirror problem.

Natural boundary element method for mixed boundary problem of circular plate

10760
Tue·14:00·B

Zhengzhu Dong,† Hui-ming Zhao and Wei-hong Peng
China University of Mining and Technology, China†

Based on Green function method and formula of general function, the boundary integral formula and natural boundary integral equation can be educed for the biharmonic equation of the bending problem of the circular plate. The matrix of coefficients can be generated by cyclic matrices. The matrices of coefficients are the same for different loads when the boundary conditions are the same. Only the right term of the equation changes according the fundamental solution and the submatrix should be properly chosen to solve for the different boundary conditions. The deflection and the angle of rotation on the boundary can be obtained directly. The method has high speed of convergence and precision. And its calculating process is relatively simple. The solution coincides exactly with that of finite element method. The problem with more complex loads can be solved by similar method or by superposition of the solution of the above-mentioned examples.

Numerical analysis on the mechanics characteristic of spot-welding-flake-strain-sensor

10964
Tue·14:05·B

Yongjun Xu,† Junwu Tang, Song Zhan and Erfei Zhao
Chinese Academy of Sciences, China†

For the disadvantage in practice to adhere the strain gauge, it is difficult to do something in adhering, curing and post curing, or the brevity of time limit for a project. Some pre-work, such as adhering, curing and post curing, some primary seal work, can be brought into laboratory by flake strain gauge/sensor technology. Then, we only need to joint the flake to the matrix in the field. Spot welding, TIG and electrical resistance spot welding can transfer the stress with a certain scale very well, meanwhile, there is not any damage on the strain gauge. A FEM calculation was carried out by using ANSYS software. The characteristic with the different parameters was analyzed, including the thickness, the gap between the flake and matrix, the size and quantity of spot welds. The numerical results were compared with the theoretical value and the transfer coefficient was obtained. All these investigations will provide a theoretical basis for the practical application of the slice sensor.

Exact solutions of frame structures

11017
Tue·14:10·B

Haitao Ma† and Taicong Chen
South China University of Technology, China†

For most linear static analysis problems of frame structures, exact solutions can be obtained by the finite element method when the shape functions used satisfy the homogenous Euler equations of potential energy functional. For dynamic and linear buckling analyses, however, meshes good for linear static solution are often too coarse and require substantial refinement to get accurate analysis results. This paper presents recent studies on the development of new finite elements and algorithms for exact solutions of natural frequency and linear buckling analysis problems. New shape functions are constructed by using general solutions to the homogeneous governing equation of the respective problem, and based on these shape functions, new finite elements are formulated. Based on the new elements, iterative algorithms for finding exact solutions for the natural frequency and linear buckling analysis problems are proposed.

Gl mechanical and electromagnetic coupled field modeling and inversion

11259
Tue·14:15·B

Ganquan Xie,† Lee Xie, Jianhua Li and Feng Xie
GL Geophysical Laboratory, USA†

We propose Global and Local (GL) Mechanical and Electromagnetic (EM) field coupled modeling and inversion. The uniform form of mechanical and EM equations is presented. Their domain is a finite inhomogeneous medium which is embedded into infinite homogeneous domain. The domain is divided to a set of sub domains. The velocity, magnetic, stress, and electric field are presented as explicit recursive sum of integrals in the sub domains. The analytical mechanical and EM field and the Green's tensor in background domain are called initial Global field. The Global field is updated by Local scattering field successively sub by sub domain. Once all sub domains are scattered , the GL mechanical and EM field solution are obtained. GL method directly assembles inverse matrix for solution and does not need to solve larger matrix equation. It does not need artificial boundary for truncating infinite domain. A GL nonlinear inversion is presented as an explicit form. .

A new rotation vector update for path-independent and strain-objective geometrically exact beam

11467
Tue·14:20·B

Susanta Ghosh† and Debasish Roy
Indian Institute of Science, India†

It is known that using rotation matrix parametrization geometrically exact beam can achieve objectivity of strain measures for arbitrarily large rotational deformations. The same is however not yet achieved with rotation vector parametrization. To accomplish the above, a new rotation vector update is proposed and used in conjunction with interpolations of relative rotations. The proposed update, which gives either the desired rotation or its complement, always returns a rotation vector with magnitude bounded by π. Hence interpolations of relative rotation vectors are used. Owing to the use of relative rotations, the strain-objectivity and path-independence are maintained in present approach.

Frequency dependent wave propagation in functionally graded materials

11615
Tue·14:25·B

Laurent Aebi,† Jacqueline Vollmann, Juerg Bryner and Jürg Dual
ETH Zurich, Switzerland†

The propagation of mechanical waves in functionally graded materials is studied numerically. A Finite-Difference Time-Domain method (FDTD) is applied in order to calculate the transient waves. The results are verified with an analytical solution. Since the system is conservative, the energy balance is used as an additional validation feature. Analytical solutions are available for a limited number of material gradients. The FDTD method permits the investigation of structures with arbitrary gradients. Particular interest is drawn on the influence of various gradient functions to the spectral response.

Multi-scale investigation of crystal plasticity

12074
Tue·14:30·B

Zhuo Zhuang
Tsinghua University, China

In this paper a clear multi-scale model is developed to solve the problem of lacking a proper continuum constitutive relationship at micrometer scale. In this model, the plastic strain rate is explicitly computed by the motion of discrete dislocations, replacing the plastic strain evolution equations in conventional plasticity theory.This model is verified by comparing with analytic results.A constitutive theory incorporating a more general strain gradient term is developed to represent a short range interaction of dislocations to predict the crystal plastic behavior at micrometer scale. The gradient term has a different physical meaning from that in MSG theory distinctly.

Deformation simulation under constant volume condition using phase field crystal method

11741
Tue·14:35·B

Tomoyuki Hirouchi,† Yoshihiro Tomita and Tomohiro Takaki
Kobe University, Japan†

We proposed a new technique for the deformation simulation using the phase field crystal (PFC) method, which keeps constant volume during deformation, and investigated the deformation behaviors of nano single crystal and bicrystal materials. We confirmed that the PFC model could reproduce the deformation simulation under the constant volume condition. Furthermore, we observed that grain boundary could be the source of dislocation emission and absorption.

Free vibration analysis of unsymmetric 6-noded element under mesh distortion

10252
Tue·14:40·B

Senthilkumar Vaiyapuri
Centre for Mathematical Modelling And Computer Simulation, India

Distortion of finite element meshes lead to poor results. Use of unsymmetric formulation offers mesh distortion immunity to some extent. To address the 2D effects of mesh distortion, the 6-noded triangular element with plane stress conditions had been developed for free vibration analysis. Two separate sets of shape functions are used in such formulation. Depending on the shape function used, the elements are classified into parametric (PP), metric (MM), parametric-metric (PM) and metric-parametric elements (MP). From the numerical tests, it had been seen that the PM element gives more accurate natural frequencies than the conventional PP element under distortion. Interestingly, the MP element results are identical to PM element results of the various types of mesh distortions for the free vibration analysis and it will be valid for all the cases with different boundary conditions under admissible distorted geometry shapes.

Numerical solution of fractional derivative equations in mechanics: advances and problems

11290
Tue·14:45·B

Wen Chen† and Hongguang Sun
Hohai University, China†

This report is to make a survey on the numerical techniques for fractional derivative equations in mechanical and physical fields, including numerical integration of fractional time derivative and emerging approximation strategies for fractional space derivative equations. The perplexing issues are highlighted, while the encouraging progresses are summarized. We also point out some emerging techniques which will shape the future of the numerical solution of fractional derivative equations.

On the nonuniqueness of BIEM/BEM using SVD

11723
Tue·14:50·B

Jeng-Tzong Chen
National Taiwan Ocean University, Taiwan

In this paper, the nonuniqueness of BIEM and BEM are studied by using SVD technique. It contains the nonuniqueness solution for degenerate boundary, degenerate scale, spurious eigenvalue and fictitious frequency. First, the influence matrices in the dual BIEM and dual BEM are constructed. Mathematically speaking, it stems from the rank deficiency of influence matrices. After employing the SVD technique with respect to the four influence matrices, it is found that true (physics) information is imbedded in the right unitary matrix while the spurious or fictitious (numerics) information appears in the left hand side. Several approaches, hypersingular formulation, SVD updating term and updating document technique, complex-valued formulation, CHIEF and CHEEF concept, were applied to ensure the unique solution. Four simple examples are demonstrated to see the validity of the present formulation.

Vibration of thick plates under in-plane loading using finite strip-elements

11128
Thu·11:00·2

Joe Petrolito† and Bruce Golley
La Trobe University, Australia†

Finite strips have been successfully used for the analysis of plates for many years. For plates with two opposite edges simply supported, the global equations uncouple into a number of smaller systems of equations, giving an increase in computational efficiency. However, uncoupling does not occur for other boundary conditions, thereby reducing the computational efficiency. In addition, the shape functions used in the finite strip method do not satisfy free edge boundary conditions. In this paper, we consider the use of finite strip-elements for the vibration analysis of thick plates under in-plane loading. Finite strip-elements combine shape functions of finite elements and finite strips. Mixed boundary conditions are simply treated, with the free edge condition being approximately satisfied as a natural boundary condition.

Micropolar cohesive zone model for delamination failure in microsystem interconnects

11193
Thu·11:20·2

Yan Zhang,† Johan Liu, Jing-yu Fan and Ragnar Larsson
Shanghai University, China†

A wide variety of advanced interconnects find application in microsystem packaging and other industries, among which anisotropic conductive adhesive (ACA) is widely used as interconnect material. The interconnect is normally a thin-layered structure with significant dimension in itself, and the delamination failure often initiates in this area. In the present paper, a homogenized interface model specifically focusing on the internal microstructure in the ACA interconnect has been developed based on micropolar theory, which is a kinematical extension of the continuum theory to properly describe the homogenized interfacial response. A representative volume element is chosen according to the typical microstructure in the ACA interconnect, and the corresponding fluctuation field is utilized to represent the microscopic variation. Especially a cohesive zone model is introduced to describe the microscopic delamination failure progress within the microstructure in the ACA interconnect.

Numerical simulation of glass fragmentation under impact using a coupled damage/decohesion model with the material point method

10912
Thu·11:40·2

Luming Shen
Monash University, Australia

In this paper a bifurcation-based simulation procedure is proposed to explore the transition from localization to decohesion involved in the glass fragmentation under impact loading. In the proposed procedure, the onset and orientation of discontinuous failure of glass is identified from the bifurcation analysis based on a rate-dependent tensile damage model. The material point method is employed to accommodate the multi-scale discontinuities involved in the glass fragmentation with a simple interface treatment. A parametric study has been conducted to demonstrate the effects of specimen size and strain rate on the evolution of glass failure under impact loading. The preliminary results obtained in this numerical study provide a better understanding of the synergistic effects on impact-resistant glass design.

Neural networks for meshless and PUFEM approaches

11394
Thu·12:00·2

Luca Facchini† and Paolo Biagini
University of Florence, Italy†

Artificial neural networks have been extensively employed to solve differential problems in mechanics, and particularly in solid mechanics. This task is usually accomplished by means of a meshfree approach coupled to a training performed by means of either a Galerkin, a collocation or a least squares approach. In order to avoid some problems connected to the fulfilment of the boundary conditions, a training based on energy methods and Hu–Washizu principle is discussed on a simple example, namely a beam with a clamped end and a simple support at the other end; such approach improves the quality of the solution employing the same number of test functions. Subsequently, following the PUFEM and Hp-Clouds Finite Element Method approaches, a quadrilateral finite element with a neural network based enrichment of the shape function is applied and discussed. The neural enrichment enables to avoid the linear dependence problems of the classical enrichment schemes.

Deformability of flexibly jointed structure with negative Poisson's ratio

11463
Thu·12:20·2

Hiro Tanaka† and Yoji Shibutani
Osaka University, Japan†

Frame structures are, in general, made up of joints and beam members, and the joint rigidity can determine their global deformation behaviors. We propose the new structural model with highly flexible joint, based on the total Lagrangian formulation under finite displacement. This formulation includes both the rigid joint as the infinitely large joint rigidity and the pinned joint as infinitely small one. Introducing the unique in-plane frame structures with negative Poisson's ratio, controllability of the ratio extending from the negative value to the positive by joint rigidity is intensively discussed. The finite displacement analyses of these structures suggest the drastic nonlinear change of the Poisson's ratio according to the joint rigidity and also the anisotropic global deformation manner.

Nonlinear coupled FE-simulation of thermoelectromechanical processes in thin-walled structure

11485
Thu·12:40·2

Ruediger Schmidt† and Sven Lentzen
RWTH Aachen University, Germany†

This work deals with a numerical example based on a previously published fully-coupled thermopiezomechanical model, with the exclusion of ponderomotoric forces and electrically induced body moments. The numerical example consists of a circumferentially hinged steel plate covered with piezoelectric layers, which is loaded by a thermal shock. The emerging coupling effects between the mechanical, electrical and thermal quantities are discussed.

Morphology change in interfacial dislocation network by prismatic dislocation loop: discrete dislocation dynamics study

11726
Fri·11:00·2

Kisaragi Yashiro,† Yoshihiro Tomita, Joy Pangetsu and Masaaki Konishi
Kobe university, Japan†

As a series study of the discrete dislocation dynamics (DDD) simulation on the interfacial dislocation network in Ni-based superalloys, we have performed DDD simulations on the interaction between the dislocation network and a prismatic dislocation loop. As previously reported in our molecular dynamics simulation, the network changes its morphology by replacing its mesh knot with the prismatic loop. The detail observation and discussion reveal that this change is caused by junction formation of three dislocations, prismatic, warp and weft of network, on the γ/γ' interface. The shape of the replaced mesh knot is same as the initial prismatic loop; however, the Burgers vector is changed in the half of the prism, i.e. the Burgers vector of the upper half of the loop is the original or parallel to the interface, while the lower is out-of-plane against the interface.

A new curved FE approach for analysis of masonry vaults

12144
Fri·11:20·2

Antonio Tralli,† Enrico Milani and Gabriele Milani
University of Ferrara, Italy†

The study of masonry vaults should take into account the essentials of the material “masonry”—i.e. heterogeneity, almost no resistance to tension combined with a good compressive strength and a high friction coefficient—as well as the overall importance of the geometry for achieving the equilibrium. It can be affirmed that the modern theory of Limit Analysis of Masonry structures, which has been developed by Heyman, is the tool to understand and analyze masonry historical vaulted structures. In the present paper the masonry texture at collapse are taken into account by a homogenization procedure and a new six-nodes curved element is developed for the kinematic limit analysis of masonry shells. In this way an upper bound of the collapse multiplier is obtained. All possible deformation modes along the element sides (rotation, stretching and sliding) are taken into account and the inelastic deformations due to bending moment, torsion, out-of-plane shear and in-plane actions are considered.

Anisotropic hyper-elastic shells using polyconvex strain energy function with application to mechanical cloth behaviour

11910
Fri·11:40·2

Masato Tanaka,† Shuya Oi, Chisato Nonomura, Sonoko Ishimaru, Kenji Furuichi, Hirohisa Noguchi and Takaya Kobayashi
Keio University, Japan†

An anisotropic hyper-elastic material model using a polyconvex strain energy function with the application to mechanical behaviour of cloth is presented. Interaction effect of each fiber is accounted for using weight factors of the principal material directions. Numerical identification of the material parameters for cloth is conducted to fit experimental data on knitted strips stretched in the warp, weft and bias directions. With this constitutive model, computation of clothing pressure applied to human body is given and the validity and efficiency of this material model are investigated.

Inverse analyses, artificial neural networks and dilatometric tests for damage and stress state assessment in concrete dams

11191
Fri·12:00·2

Giulio Maier,† Tomasz Garbowski, Giorgio Novati and Ada Zirpoli
Politecnico di Milano, Italy†

In dam engineering the assessment of possibly deteriorated material properties and of the stress state in dam concrete is necessary for computations of structural safety margins. A new method is proposed herein to achieve such purpose locally, in depth and in an inexpensive and non-destructive way. This diagnostic method, derived from traditional overcoring techniques and dilatometric tests in rock mechanics, is centered on inverse analysis and makes it possible to identify in depth a number of parameters which quantify the concrete behavior in the linear and nonlinear range and the stress state. For repeated applications of the proposed technique, the adoption of artificial neural networks is envisaged: accurate nonlinear finite element modeling is thus performed once for all only, in order to generate by the 'forward' operator a suitable number of 'patterns' for 'training' and 'testing' the neural networks, to be later economically employed on a portable computer on site.

SM02 :: Contact and friction mechanics

Chairs: Irina Goryacheva (Russia) and Peter Wriggers (Germany)

Mon	14:00–16:00	Room 4	Lectures
Tue	14:00–14:30	Room 10	Seminars
Thu	16:00–17:00	Room 4	Lectures

A class of dynamic contact interaction problems in viscoelasticity

10227
Mon·14:00·4

Marius Cocou,[†] Mathieu Schryve and Michel Raous
Laboratoire de Mecanique et d'Acoustique CNRS, France[†]

The aim of this work is to study an interaction law combining reversible adhesion, friction and unilateral contact between two viscoelastic bodies of Kelvin–Voigt type. We first consider classical formulations for this new class of dynamic problems. We then analyse the corresponding variational formulations, written as systems of evolution implicit variational inequalities which describe the bulk and the surface behaviours, including a parabolic variational inequality which describes the evolution of the intensity of adhesion. The techniques based on penalty methods and incremental approaches, used previously to study dynamic unilateral contact with nonlocal friction for viscoelastic bodies and for a cracked viscoelastic body, are developed here in order to analyse the variational problems. Finally, some numerical examples are presented.

Effect of adhesion in sliding contact of rough bodies

10537
Mon·14:20·4

Irina Goryacheva[†] and Yuliya Makhovskaya
Russian Academy of Sciences, Russia[†]

The model is developed to study the effect of adhesion in sliding contact of elastic and viscoelastic bodies with rough surfaces. It is based on calculating the energy dissipation for each formation and breaking of an elementary contact between two asperities. The dependences of the contact characteristics and resistance force on the surface energy of the interacting bodies, their mechanical properties, and microgeometry of the surfaces are calculated and analyzed. The combined effect of hysteretic losses and adhesion on friction force in sliding contact of viscoelastic bodies is also investigated.

Contact analysis with non-linear elasticity and combined cone/spherical indenter

10750
Mon·14:40·4

Pauli Pedersen
Technische Universität Denmark, Denmark

A method for direct contact analysis without incrementation and iteration, valid for linear elasticity, is extended to obtain solutions for problems involving non-linear elasticity. The extension is based on updating the element stiffness matrices and convergence is obtained in about 10 iterations. With application to indentation problems the study includes influence from Poisson's ratio in addition to the influence from the power of the non-linear elasticity. Furthermore, the influence from the shape of the combined cone/spherical indenter is reported.

Influence of contact geometry on hardness values **10946** Mon·15:00·4

Weimin Chen,† Che-Min Cheng, Yang-Tse Cheng and Min Li
Chinese Academy of Sciences, China†

Hardness is presently measured using nominally sharp indenters and on flat surfaces. The influence of contact geometry, including the finite curvature of the indenter tip and the roughness of the specimen, on hardness behavior for elastic plastic materials is studied by means of finite element simulation. We idealize the actual indenter by an equivalent rigid conic indenter fitted smoothly with a spherical tip and examine the interaction of this indenter with both a flat surface and a rough surface. Materials studied are either elastic perfectly plastic material or strain hardening. Our results show that depending on the material properties the finite curvature of the indenter tip causes the hardness value to rise or drop as the indentation depth decreases. Surface asperities and dents can appreciably modify the hardness value at small indentation depth. Their effects would appear as random variation in hardness. These results are helpful in interpreting hardness measurements.

Dynamic effects of a sliding tread block on concrete surfaces **10600** Mon·15:20·4

Patrick Moldenhauer,† Matthias Kröger and Gunnar Gäbel
Technische Universität Bergakademie Freiberg, Germany†

The task of tyres is to transmit all normal, longitudinal and lateral forces between vehicle and road. One basic part of the tyre is the tread pattern which is in direct contact with the road surface and thus is in general responsible for the traction level of the whole tyre. The dynamic behaviour of a tyre tread block is described by a modularly arranged model. Special emphasis is laid on the interaction between the structural dynamics and contact mechanics. In the simulation the rough surface on which the tread block slides is modelled as smooth with the friction characteristic of the respective material pairing and a non-linear description of the local tyre/road interaction. This leads to an adequate description of the contact partners without losing numerical efficiency. Furthermore the model considers wear that changes the block geometry and thus the vibrational behaviour. Dynamic effects like friction induced vibrations are simulated with the presented model.

Adhesion of elastic spheres: finite element modeling, Derjaguin approximation **11637** Mon·15:40·4

Harish Radhakrishnan† and Sinisa Mesarovic
Washington State University, USA†

In this work we focus on the development of a finite element model to analyze the adhesive contact between two elastic spheres. The hallmark of the finite element model is the use of a local contact model which allows the study of the implications of the Derjaguin approximation—a feature embedded in the existing models of adhesion. Results from the finite element analysis show that the Derjaguin approximation is valid for small, stiff spheres with weak adhesion but fails for large, compliant spheres with strong adhesion. The failure to account for the rotations of interacting surfaces just outside the contact area is the primary factor.

10700
Tue·14:00·10

Two smoothing methods in frictional beam-to-beam contact: a numerical comparison

Przemyslaw Litewka
Poznan University of Technology, Poland

In this paper two methods to construct smooth curves for the 3D beam-to-beam contact analysis are compared. While they are both based on Hermite polynomials, a difference lies in the number of beam nodes involved to obtain a segment of a smooth curve. It is also important to note that one of these methods yields the curve which does pass through the parent nodes, which is an important aspect contributing to the accuracy of the FE model. Both the curve construction types are embedded in the frictional beam-to-beam contact formulation. The resulting tangent stiffness matrices and residual vectors have different dimensions and the computer time of the analysis is different. On the basis of several numerical examples, one of which is presented herein, it is concluded that the node preserving method is to be preferred due to its accuracy in approximating of a real curve representing a beam.

11673
Tue·14:05·10

Micro/nanoscale friction and its dependence on contact area

Sriram Sundararajan,[†] Kanaga Karuppiah and Angela Bruck
Iowa State University, USA[†]

The friction behavior of mica and ultra-high molecular weight polyethylene (UHMWPE), was evaluated at the nanoscale with an atomic force microscope (AFM) and at the microscale with a custom-built microtribometer. The same counterface (Si_3N_4 probe) and environmental conditions (25°C, RH $<$ 10%) were maintained for all experiments. Friction on mica at the nanoscale showed initial non-linearity with normal load up to a certain load, beyond which surface damage was observed resulting in a linear dependence of friction on normal load. At the microscale, the friction on mica exhibited linear dependence. Friction between Si_3N_4 and UHMWPE exhibited non-linearity at both the length scales, for the applied load ranges of our experiment. Upon calculating an interfacial shear strength value for the material pair (using appropriate contact mechanics theories), we found that the values at both the scales were comparable, when the conditions were carefully maintained to be the same across scales.

12070
Tue·14:10·10

A new contact width model for an automatic polishing process

Wei-Ling Kuo[†] and Ming Tsai
National Cheng Kung University, Taiwan[†]

A new mathematical model to predict the contact width for a rubber polishing roller tool is postulated. A correlation between Hertz contact curve and normal Gaussian distribution curve has been derived. Experiment shows that the contact width calculated by the Hertzian equation gave too big an error to be used in an automatic polishing system. The new contact width model gave much better results.

Connected models of friction of rolling, sliding and whirling in problems of solids dynamics

10181
Tue·14:15·10

Alexey Kireenkov
Institute for Problems in Mechanics, RAS, Russia

It is presented a new approach for dry friction modeling under conditions of combined kinematics. The main distinguish feature of this approach is building of rheological models which are suitable for using in differential equations of motion. Proposed models involve the replacement of exact integral expressions for the net vector and torque of the dry friction forces, by appropriate Pade approximations. This approach substantially simplifies the combined dry friction modeling, making the calculation of double integrals over the contact area unnecessary. Moreover, one does not have even to calculate the integrals to determine the coefficients of the Padé approximation. The corresponded coefficients can be identified from experiments. One of the main advantages of proposed models is obviating a necessity to solve the problem of the theory of elasticity and exactly define the boundaries of area of contact.

Analytical solution of the spherical indentation problem for a half-space with functionally graded elastic coating

10667
Tue·14:20·10

Sergey Aizikovich,† Irina Trubchik, Leonid Krenev and Viktor Alexandrov
Don State Technical University, Russia†

In their work the authors consider contact problem for the penetration of spherical indenter into a half-space with functionally graded coating (it is assumed that the Lame coefficients vary in arbitrary way with the coating depth); reduce problem to dual integral equations and develop analytical methods which makes it possible to achieve stable numerical results while analyzing the mechanical properties for functionally graded coating with alternating sign gradient in elastic properties; study the variation effect in elastic properties on the maximum stresses in the surface layers of materials with graded coatings caused by spherical indentation. The developed methods allow constructing analytical solutions with presupposed accuracy and giving the opportunity to do multiparametric and qualitative investigations of the problem with minimal computation time expenditure.

On plane contact problems under partial reverse slip condition

11855
Tue·14:25·10

Haradanahalli Murthy† and Naseem Hamza
Indian Institute of Technology, Madras, India†

Non-sliding boundary value problems of contact between two elastic half spaces are under either “partial slip” or “partial reverse slip” conditions depending upon applied tangential loads (tangential force at interface and bulk stresses). If tangential force dominates, direction of slip is same in both the slip zones (partial slip). If bulk stress dominates, slip is in one direction at one edge and in opposite direction at the other edge of contact (partial reverse slip). A general shear traction distribution, based on boundary conditions and the direction of slip in slip zone, has been proposed to solve the plane contact problems under partial reverse slip conditions. Muskhelishvili’s approach is used to invert Cauchy type SIE to obtain shear traction. Closed form expressions for determining ends of stick zone have been obtained. Shear traction has been evaluated for partial reverse slip contact of two geometries on flat half space: a) cylindrical punch, b) nominally flat punch.

Contact vibration analysis of an elastic-sphere oscillator and a semi-infinite viscoelastic cubic solid

10606
Thu·16:00·4

Jiayong Tian† and Zhoumin Xie
Institute of Crustal Dynamics, China†

Resonant-ultrasound microscopy evaluates local Young's modulus of materials by the resonant-frequency shift of a vibrating oscillator. This study presents a dynamic-contact model to analyze free vibrations of an isotropic elastic-sphere oscillator contacting a semi-infinite viscoelastic cubic solid. Assuming frictionless contacts and smaller vibration amplitude, dynamic-contact pressure distributions between the sphere and the solid are obtained. Combining the sphere oscillation and the solid motion through contact-displacement boundary conditions yields resonant frequencies of the sphere. Unlike the quasi-static model, the result of this dynamic model agrees well with the measurements using an electromagnetic-acoustic-transduction method, which will benefit quantitative evaluation of surface elastic stiffness in resonant-ultrasound microscopy.

Three-dimensional contact of rough bodies by multiply-connected domain

10343
Thu·16:20·4

Ganna Shyshkanova
Zaporizhzhya National Technical University, Ukraine

Machine parts have complex geometric shape according to their design; also they can change the shape in some limits during the production process and operating. So, in most practical cases, the contact domain has shape different from circle or ellipse. The numeric-analytical method is proposed for the problem about contact interaction of two bodies initially touched in a point or close line, indentation of multiply-connected punches into elastic half-space accounting linear, nonlinear friction and roughness laws. The problem leads to solution of two-dimensional integral equations containing integrals of simple fiber potential type. The solution is based on small parameter expansion, regularization, cubature formulae. When the contact domain is nonsymmetrical because of bodies shape or influence of friction, the calculation of simple fiber potential with nonsymmetrical density distribution is made performing expansion by Legendre's polynomials. The method is convenient for practice.

Friction mechanism of an elastomer sliding on smooth surface: influence of water squeeze film

10900
Thu·16:40·4

Deleau Fabrice,† Koenen Alain and Mazuyer Denis
Laboratoire de Tribologie et Dynamique des Systmes, France†

The wiping of a car windshield is carried out with the reciprocating motion of a rubber blade. This function is realized by a contact between rubber lip and glass of very small dimension (few tens of micrometres). The analysis of this contact requires a better understanding of the frictional response. This paper analyses the tribological behaviour of micrometer rubber spots sliding on a smooth surface. These aspects have been investigated at the nanometer scale using the resources of a modified elasto hydrodynamic tribometer. A small rubber cylinder is loaded on a rotating disk and the interface is visualized by interferometric technique. Our experiments propose to simulate the rubber/glass contact with a complete instrumentation to analyse the sliding steady state behaviour in dry and wet condition. The experiments give direct access to the solid contact area contribution to friction stress in both wetting conditions in order to explain the friction mechanism.

SM03 :: Control of structures

Chairs: Felix Chernousko (Russia) and Andre Preumont (Belguim)

Thu	11:00–13:00	Room 1	Lectures
Thu	14:45–14:55	Hall C	Seminars

Design of resonant vibration absorbers with filtered feedback **10899** Thu·11:00·1

Steen Krenk† and Jan Hogsberg
Technical University of Denmark, Denmark†

A procedure is proposed for optimal parameters in two different second order filter implementations of resonant vibration absorbers. Each filter contains four parameters: a resonance frequency and a damping ratio, as well as two coupling parameters. The resonance frequency is determined from the complex root locus. The amplification curve contains two fix points, where the amplification is independent of the damping ratio of the absorber. Equal amplification at these points is used to eliminate one of the coupling parameters. Finally, the damping ratio is determined by imposing the same amplification at an intermediate frequency. This leaves one parameter, serving as the gain of the vibration absorber. The design is near-optimal and leads to nearly even reduction of the response and a flat maximum of the control force.

Controlled onset of low-velocity collisions in vibro-impacting systems with friction **11065** Thu·11:20·1

Harry Dankowicz† and Fredrik Svahn
University of Illinois at Urbana-Champaign, USA†

This paper presents a control strategy aiming to regulate the onset of low-velocity collisions in an example vibro-impacting system with dry friction. The proposed strategy is shown to successfully differentiate between continuous transitions in which a stable periodic oscillation persists to the limit of zero contact velocity and discontinuous transitions in which no stable oscillations can be found in this limit. It is argued that the discontinuous scenario affords a means for directed energy transfer and damping triggered by sufficiently large oscillation amplitudes and, consequently, that control may be used to suppress such energy loss associated with the onset of low-velocity collisions. The proposed control strategy is inspired by related work on the control of near-grazing dynamics in vibro-impacting systems in the absence of friction in that stabilization of the low-contact-velocity oscillations is achieved by purposeful exploitation of the effects of system discontinuities.

A variational approach to 3D rod motion modeling and optimization **11464** Thu·11:40·1

Georgy Kostin† and Vasily Saurin
Institute for Problems in Mechanics RAS, Russia†

The initial-boundary value problem for the linear theory of elasticity is considered. Based on the method of integrodifferential relations a new dynamical variational principle in which displacement, stress, and momentum functions are varied is proposed and discussed. To minimize the nonnegative functional under initial, boundary, and partial differential constraints arising in this approach a regular algorithm for approximation of the unknown functions is worked out. The algorithm gives us the possibility to estimate explicitly the local and integral quality of obtained numerical solutions. An effective numerical approach to optimal control problems of elastic structure motions is developed. As example, the 3D problems of optimal longitudinal motions of a rectilinear elastic rod with a quadratic cross section are considered for the terminal total mechanical energy to be minimized. The numerical results and their error estimates are presented and discussed.

Mobile systems controlled by internal moving masses

10538
Thu·12:00·1

Felix Chernousko
Russian Academy of Sciences, Russia

It is well-known that a body containing internal masses can move in a resistive medium, if the internal masses perform special motions relative to the body. Progressive motions of a body controlled by internal moving masses are considered for various kinds of resistance forces acting upon the body: linear, quadratic resistance, and Coulomb's dry friction forces, both isotropic and anisotropic. Special periodic motions of the internal masses are analyzed under constraints imposed on relative displacements, velocities, and accelerations of these masses. Optimal relative motions of the internal masses are determined that correspond to the maximal average speed of the system as a whole. Experimental data confirm the obtained theoretical results. The principle of motion discussed in the paper does not require outward devices such as screws, wheels, etc. and can be used for mobile robots, especially mini-robots, moving in tubes, corrosive media, and complex environment.

Optimum control of thermal stress in a piezo-composite disk

11213
Thu·12:20·1

Fumihiro Ashida,[†] Naotake Noda and Sei-ichiro Sakata
Shimane University, Japan[†]

This paper deals with a control problem of a thermal stress in a multilayer composite circular disk consisting of a structural layer onto which piezoceramic layers are bonded. A number of electrodes are concentrically arranged on each piezoceramic layer. When a heating temperature distribution acts on the structural layer, the maximum thermal stress in the structural layer is controlled by applying appropriate voltages to the electrodes. This thermoelastic problem is theoretically analyzed using the potential function techniques proposed by the authors. Utilizing the analytical results, a nonlinear optimization problem for determining the applied voltages is transformed into a linear programming problem, and the optimum solution is successfully obtained. The structure of a composite disk is then designed in order to demonstrate the function of stress control to the fullest extent possible. It is seen from the numerical results that the maximum thermal stress can be reduced by 33.7%.

Equilibrium stabilization via position and delayed position feedback

11052
Thu·12:40·1

Haiyan Hu[†] and Bo Liu
Beijing Institute of Technology, China[†]

The paper presents a systematic approach to stabilize the unstable equilibrium of a system of multiple degrees of freedom by using both Position and Delayed Position feedbacks. The approach features allocating an infinite number of eigenvalues of such a system. For a fully-actuated system, the approach enables one to design the controller via the modal decoupling and a stability chart. For an under-actuated system, the approach includes two steps. The first step is to move all the eigenvalues of the system on the imaginary axis by using a position feedback, and the second step is to drag all the eigenvalues to the left half open complex plane by using a delayed position feedback according to the sensitivity analysis of eigenvalues. The stabilizations of a fully-actuated robotic manipulator and an under-actuated double-inverted pendulum are discussed respectively to demonstrate the controller design for two different types of unstable systems and to support the efficacy of the approach.

The adaptive spatial mobile robot-manipulator and way of diagnostics of physical and mechanical properties and the geometrical form of a surface of contact and trajectory of movement with his help

11555
Thu·14:45·C

Sergey Sayapin[†] and Alexander Siniov
Mechanical Engineering Research Institute, Russia[†]

The new concept of the robot-manipulator is submitted. The device concerns to spatial intellectual structures of modular type. Each of modules is executed as an octahedron. All ribs of an octahedron are executed as rods with linear drives. The ends of rods have swivel-connections in tops of an octahedron. Tops of the module and midst of parallel rods are supplied with radial clamps with an opportunity of formation adaptive clamps and fixing support of the robot-manipulator. Each of cores is supplied with gauges of linear moving and speed. Radial clamps are supplied with gauges of force. In tops of an octahedron are established three-axial blocks of accelerometers. In structures consisting of three and more modules the general sides are parallel among themselves. The offered concept can be realized at a macrolevel and at a microlevel and be applied to operation in ground, underground, underwater, aerospace techniques, medicine and instrumentation.

Distributed control of plate vibrations induced by in-plane time-dependent forces

10235
Thu·14:50·C

Andrzej Tylikowski
Warsaw University of Technology, Poland

A theoretical investigation of vibration control for linear elastic plate due to arbitrary varying in time in-plane forces is presented. In order to stabilize induced transverse vibrations the host structure is integrated with a control system consisting of piezoelectric sensors and actuators. A distributed controller consisting of electroded piezoelectric sensors/actuators with a suitable polarization profile is considered. Assuming the negligible stiffness of polymer sensors the voltage applied to the actuator electrodes is obtained using PD controller. The almost-sure asymptotic stability criteria involving a damping coefficient and loading characteristics are derived using Liapunov's direct method. The energy-like Liapunov functional is assumed in the form of a sum of modified kinetic energy and potential energy of the plate as well as an energy of electric field in piezoactuators.

SM04 :: Damage mechanics and fatigue

Chairs: Nikita Morozov (Russia) and Romesh Batra (USA)

Tue	14:35–14:55	Room 10	Seminars
Tue	16:00–17:40	Room 4	Lectures
Thu	09:15–10:35	Room 3	Lectures

High rate loading and unexpected phenomena

10540
Tue·14:35·10

Nikita Morozov,† Yuri Petrov and Lavrenti Shichobalov
St Petersburg State University, Russia†

The problems involving high and ultra-high rate loading belong to problems that are insufficiently investigated to the moment. Recent experiments provide new results that are often unexpected and unexplainable in the framework of generally accepted approach to the problem. In the report an unexpected phenomena taking place whilst sample at elevated temperature is impact loaded will be discussed and an explanation of processes underlying dynamically loaded sample at temperatures close to one of melting will be given.

Life prediction based on crack growth analyses in different microstructures modeled by Voronoi-polygons under biaxial fatigue

10734
Tue·14:40·10

Toshihiko Hoshide,† Atsushi Kasai and Naoya Takahashi
Kyoto University, Japan†

In this work, microstructures of a few materials are modeled by using Voronoi polygons, and a modeling of slip band formation by crystallographic sliding in individual grains constituting a modeled microstructure is proposed for the crack initiation analysis. The algorithm for the crack growth is also established as a competition between the growth by crack linkages and the propagation of a dominant crack as a single crack. The cracking morphology is simulated using the proposed model with a Monte Carlo procedure. The fatigue life is statistically predicted based on the crack growth behaviour simulated for various microstructure configurations, which are generated by randomizing Voronoi polygons for a material under consideration. By comparison of simulated results with experimental observations in fatigue tests of a few materials, cracking morphology and failure life are found to be well simulated by using the proposed model.

Anisotropic damage participation in online hybrid testing application

11765
Tue·14:45·10

Abdulfatah Souid,† Arnaud Delaplace and Frederic Ragueneau
LMT-Cachan, France†

The comprehension of the ultimate failure of a structure can be approached in two ways: the experimental testing and the numerical modelling. Laboratory experimental testing gives accurate information if realistic dimensions and pertinent boundary conditions are used. Numerical simulations can be used to compute structure failure, at least at a low damage level. But robust, universal, models are still needed to achieve such simulations, particularly for ultimate behaviour. Hybrid pseudodynamic testing allows to test statically a real scale parts of structures in parallel to the modelling of other structural parts under seismic loading. We present here one of such testing conducted on reinforced concrete structure. Originalities of the present work are mainly the using of an anisotropic damage model to simulate the concrete bahaviour of the modelled substructures, and the using of digital image correlation technique to study the different collapse modes of the tested substructure.

An analytical model for frictional load transfer in a clearance fit bolted joint

11033
Tue·14:50·10

Ligieja Paletti,† Calvin Rans and Rinze Benedictus
Technische Universität Delft, Netherlands†

Experimental evidences on coupons and real structures of bolted joint shows that cracks can nucleate at two different locations. The load transfer mechanism acting in the joint is considered to be the prevalent parameter for the shift of location. If the prevalent mechanism is bearing, cracks are likely to start at the hole edge; if the frictional mechanism is predominant, cracks will appear remote from the hole. Exiting analytical models for load transfer in mechanically fastened joints typically neglect the contribution of friction. An analytical model which can determine the relative contributions of friction and bearing to load transfer is necessary in order to relate failure location to joint design. In this study, a model for the load transfer in double-shear, clearance fit, bolted joint is presented. Given the clamping pressure distribution, it is possible to determine the percentage of load transferred by the two mechanisms respectively.

Phenomenological approach to the description of deformation and fracture of damaged solids

10619
Tue·16:00·4

Evgeny Lomakin† and Tatiana Beliakova
Lomonosov Moscow State University, Russia†

The influence of damage on the material properties is studied. The deformation properties of the materials containing microcracks, pores, inclusions depend on the type of external forces because the behaviour of these inhomogeneities depends substantially on the conditions of loading or deformation. Hence, the deformation properties of these materials are stress-state-dependent ones, and this effect becomes more noticeable as the volume content of damage increases. Distributions of stress, strain and displacement occuring at a crack tip in a material with properties dependent on the type of loading are investigated for the conditions of plane strain in both far tensile and shear loads. The asymptotic solutions of crack problems are obtained on the basis of proposed constitutive relations. The influence of stress-state sensitivity of material properties on the values of the stress intensity factors is studied. The opening of the crack surfaces in the case of far shear field is observed.

Damage evolution in explosion of a particulate composite circular cylinder

10541
Tue·16:20·4

Romesh Batra† and Anoop Varghese
Virginia Tech, USA†

We study damage evolution in a particulate composite circular cylinder with ends open, and shock pressures applied either to its inner or to its outer cylindrical surfaces; results for only explosion are discussed below. Three-dimensional coupled thermo-mechanical deformations of the cylinder, comprised of tungsten (W) particulates perfectly bonded to nickel-iron (NiFe) matrix, are analyzed. Each material is assumed to be isotropic, micro-porous, heat-conducting and thermo-elasto-visco-plastic with the yield surface expanding with an increase in strain hardening and strain-rate hardening, but shrinking with an increase in thermal softening and damage or porosity. Young's and bulk moduli, and thermal conductivity decrease with an increase in the porosity. The porosity evolves due to plastic deformations and a strain-based relation for the nucleation of voids. The temperature increases due to the heat generated because of plastic working.

Analytical correlations between the fatigue properties of engineering materials

10693
Tue·16:40·4

Marco Paggi† and Alberto Carpinteri
Politecnico di Torino, Italy†

A phenomenological description of the fatigue life of engineering components can be given either by plotting the applied stress range as a function of the total number of cycles to failure, i.e. according to the Wohler curve, or, after the advent of fracture mechanics, by plotting the crack growth rate in terms of the stress-intensity factor range, i.e. using Paris' curve. In this work, an analytical approach is proposed for the study of the relationships existing between Wohler's and Paris' curves. Paying special attention to the limit points of such curves defining the range of validity of the power-law relationships, whose co-ordinates are referred to as cyclic or fatigue properties, alternative expressions for the classical laws of fatigue are proposed. Finally, the correlations between such fatigue properties are determined according to theoretical arguments, giving an interpretation to the empirical trends observed in the material property charts.

Evaluation of damage development in piezoelectric ceramics under repeated mechanical loading

10800
Tue·17:00·4

Mamoru Mizuno,† Nozomi Odagiri and Mitsuhiro Okayasu
Akita Prefectural University, Japan†

Piezoelectric ceramics are used in sensors, actuators, transducers, etc., under cyclic loading. So that, internal damage develops in certain cases and it leads to final fracture at worst. The damage causes change in material properties and a resonance frequency. Therefore, variation of material properties can be evaluated by the resonance frequency, and the internal damage can be evaluated by the variation of material properties reversely and non-destructively. In the present paper, circular rod specimens of piezoelectric ceramics were subjected to compressive mechanical loading repeatedly and the fatigue life was clarified experimentally. At the same time, material properties of the specimen were evaluated by the resonance frequency up to the fatigue fracture and variation of material properties was clarified. Then the development of internal damage in the specimen was evaluated by the variation of elastic coefficient as a damage variable based on the continuum damage mechanics.

Modelling progressive dynamic damage in advanced re-entry space transportation composite/hybrid structures

10792
Tue·17:20·4

Javid Bayandor,† Bob Farahmand and Frank Abdi
Royal Melbourne Institute of Technology, Australia†

Understanding intricate and non-linear dynamic responses of advanced aerospace composite structures is imperative in modern space vehicle safety design to eradicate or minimise damage or to control the failure sequencing. Detailed crashworthiness modelling techniques, to allow accurate prediction of failure and damage tolerance in advanced composite/hybrid structural concepts, are still in their early development stages. This is predominantly the case for discretised full-scale modelling approaches for scenarios involving severe dynamic loading conditions. Examples of such cases are those incidences observed during medium to high velocity soft impact events exerted by FOI during the atmospheric flight window of re-entry space vehicles, in particular, during the launch phase. The current study aims at perfecting a methodology to contribute to fail-safe design strategies for the future means of space transportation.

Residual strength based lifetime prediction of composite materials subjected to spectrum loading

10168
Thu·09:15·3

Scott Case,† John Lesko, Jason Cain and Nathan Post
Virginia Tech, USA†

Previous studies have shown that composite material residual strength and fatigue lifetime due to variable amplitude loading may be dependent on the load sequence. In this paper, we present results from a study that experimentally characterizes the fatigue behavior of an E-glass/vinyl ester composite as a function of autocorrelation, a statistical measure of the randomness of the loading. Nominally fully reversed Rayleigh distributed loading histories with different autocorrelations from highly correlated to completely random were applied to coupon specimens. The results show that under these conditions, load order does not significantly impact fatigue life.

Modeling of hydrogen embrittlement of metals in wet H_2S containing environments

10421
Thu·09:35·3

Vladimir Astafiev
Samara State University, Russia

Governing equations for elastic-plastic material describing the damage accumulation and fracture under hydrogen embrittlement (HE) conditions are presented. Scalar damage parameter and damage evolution equation is proposed. The proposed governing equations describe such features of HE as threshold stress, below which no failure occurs; the change of failure surface mode during HE; the delayed behavior of fracture, the existence of threshold stress intensity factor, etc. The determination of material constants from available experimental data is proposed.

Mean stress effect and bi-axial fatigue of structures from two scale damage model

10987
Thu·09:55·3

Gregory Barbier,† Stephan Courtin, Alban du Tertre, Jean-Philippe Sermage, Bumedijen Raka and Rodrigue Desmorat
École Normale Supérieure de Cachan, France†

On the idea that fatigue damage is localized at the microscopic scale, a scale smaller than the mesoscopic one of the Representative Volume Element (RVE), a three-dimensional two scale damage model has been proposed for High Cycle Fatigue applications and extended to anisothermal cases and to thermo-mechanical fatigue. A post-processor, DAMAGE, for damage and fatigue has been developped. In addition of the modelling of microdefects (or microcracks) closure by means of a microdefects closure parameter h in the expression of the energy density release rate, the consideration of the first stress invariant in the microscale plasticity criterion makes the post-processor DAMAGE able to take into account mean stress effect in calculations. A 2D testing specimen has been designed thanks to this post-processor for crack initiation for biaxial loading. Two materials are studied: titanium alloy and AISI 304L steel. Image correlation is used to follow crack initiation. Experimental and theoretical number of cycles to rupture are in good agreement. Financial support by EDF R&D, AREVA NP, Snecma Space Engine Division SAFRAN Group and CNES.

Finite element simulation and life prediction of thermal fatigue failure of the continuous casting tundish cover

11336
Thu·10:15·3

Xia Zhou,† Zhanfei Tang and Guohui Qu
Dalian University of Technology, China†

In this paper, temperature and stress fields of the continuous casting tundish cover were calculated by using ANSYS finite element method based on the physical description of its thermal fatigue failure. The relationship between the fatigue damage and stress field of the critical point was also analyzed. Besides, the temperature, stress, strain and failure process of the tundish cover were reproduced through ANSYS finite element simulation and fatigue life analysis technology, the finite element model and the solving conditions were determined. Thus, a fatigue life prediction method is proposed on the basis of the failure experiment and finite element analysis, at the same time, thermal fatigue damage mechanism and its influencing factors are discussed. The research results indicate that the solving conditons for the finite element computation of the stress field are accurate and the life prediction method is advisable.

SM05 :: Elasticity

Chairs: Reinhold Kienzler (Germany) and Gérard Maugin (France)

Tue	10:40–12:40	Room 4	Lectures
Tue	14:00–15:00	Hall D	Seminars
Tue	16:00–17:40	Hall B	Lectures
Thu	09:15–10:35	Room 4	Lectures
Thu	14:00–14:25	Hall C	Seminars
Fri	09:15–10:35	Room 4	Lectures

Nonlinear bulk strain waves in layered elastic waveguides with delamination: theory and experiments

11385
Tue·10:40·4

Karima Khusnutdinova,[†] Galina Dreiden, Alexander Samsonov and Irina Semenova
Loughborough University, UK[†]

We study the dynamics of nonlinear bulk strain waves in delaminated, layered elastic structures. First, we consider a symmetric two-layered bar and assume that there is a perfect interface when $x < 0$ and complete debonding when $x > 0$, where the axis Ox is directed along the bar. We develop an approach for finding the weakly nonlinear solution to the problem, and consider in detail the case of an incident solitary wave. We show that delamination can lead to the fission of an incident solitary wave, and we obtain formulae for the number, amplitudes, velocities and positions of the secondary solitary waves. Then, we generalize these results to the case of a symmetric n-layered bar. The theory is confirmed by successful experimental research, demonstrating the change of the amplitude and width of a strain solitary wave propagating in two- or three-layered polymeric waveguides. The research is supported by the EPSRC grant EP/D035570/1.

Plane waves in nonlinear anisotropic elasticity

11406
Tue·11:00·4

Wlodzimierz Domanski
Polish Academy of Sciences, Poland

We study propagation and interaction of nonlinear elastic plane waves in anisotropic materials. The general form of equations for such waves in an arbitrary crystal is derived. An asymptotic method of weakly nonlinear geometric acoustics is then used to derive evolution equations for plane waves' amplitudes. New evolution equations are obtained for quadratically nonlinear coupled shear waves propagating along special directions in crystal. Tables of interaction coefficients revealing possibility of all quadratically nonlinear interactions between different waves for different directions in crystals are also displayed.

Propagation of magnetoelastic waves in a vortex field in a superconducting layer

10674
Tue·11:20·4

Bogdan Maruszewski,† Andrzej Drzewiecki, Bogdan Maruszewski and Roman Starosta
Poznan University of Technology, Poland†

Magnetic field enters the type-II superconducting body along a discrete arrangement of magnetic vortex lines. In the dynamic case when the magnetic field vary in time, around each such a line a supercurrent flows. So, the vortices interact one to another with the help of the Lorentz force forming this way a new mechanical field of elastic properties. Moreover, those lines arrange themselves in a triangular or quadratic lattice. Such a set is observed if the intensity of the applied to the material magnetic field is close to its lower limiting value. The paper aims at investigating the dispersion and amplitude distributions of magnetoelastic waves propagating solely in the vortex field of the superconducting layer. Our attention have been focused on the layer thickness on the dispersion features and amplitudes for various wave velocities. The vortex field consists only of soft vortices (the superconducting crystal is free of lattice defects).

Reciprocity relations in Newtonian and Eshelbian mechanics

10542
Tue·11:40·4

Reinhold Kienzler
University of Bremen, Germany

Betti's reciprocity theorem states that the work of a force at point 1 in the displacement produced by a force at point 2 equals the work of the force at point 2 in the displacement produced by a force at point 1. The theorem is merely a consequence of the fact that the energy in an elastic body subjected to these two physical forces is independent of the sequence of their application. Recently, a similar theorem has been established in configurational mechanics involving material translations of two defects. In the paper, reciprocity relations will be given establishing reciprocity between physical forces and material translations and thus coupling Newtonian and Eshelbian mechanics. It turns out that the analysis of the mixed problem is more involved than the corresponding analysis in the strictly physical or strictly material space, and even requires an order-of-magnitude estimation. Some illustrative examples are discussed and suggestions for possible experiments are made.

Numerical analysis of stress singularity in three-dimensional problems of elasticity theory

11384
Tue·12:00·4

Valeriy Matveyenko,† Tatyana Nakaryakova and Natalya Sevodina
Institute of Continuous Media Mechanics, Russia†

This paper introduces a new numerical method of constructing eigen-solutions for polyhedral wedges and cones, which provide insight into the character of stress singularities at the vertexes of the examined region, and considers the key aspects of its numerical realization. The results of performed experiments lend support to the validity and reliability of the proposed method. The paper presents the results of solution of several example problems, some of which have been solved for the first time. In particular the obtained results provide information on the character of stress singularity at the vertexes of the following three-dimensional problems: trihedral wedge, circular cone, full cone, composite cone with an elliptical base. Numerical results have been obtained for different versions of the boundary conditions at the lateral surfaces and various parameters specifying geometry of the considered bodies and elastic properties of the material.

Materials with Poisson's ratio near -1: properties and possible realisations

11982
Tue·12:20·4

Elena Pasternak,† Arcady Dyskin and Elena Pasternak
The University of Western Australia, Australia†

A method of designing microstructures with negative Poisson's ratio is proposed based on connecting the constituencies with links having high ratio of shear to normal stiffness. In particular, such situation can be achieved by stiff gluing of thin spherical shells. In this case the low normal stiffness is ensured by low bending stiffness of the shell, while its shear resistance can be kept relatively high. As the ratio between the shell thickness and radius tends to zero, the Poisson's ratio tends to -1. In this limit the material becomes insensitive to body forces such as the self weight, as they create negligible stresses. The stress wave velocities tend to infinity and in the limit of the Poisson's ratio equal to -1 the waves disappear. This suggests the possibility of high vibration energy absorption.

The Flamant and Carothers type problems for cusped prismatic shells

10023
Tue·14:00·D

George Jaiani
Ivane Javakhishvili Tbilisi State University, Georgia

The paper deals with the zero approximation of I. Vekua's hierarchical models of prismatic shells, when the thickness of the shell varies as a power function of one argument and vanishes at the cusped edge of the prismatic shell. The problem, when the prismatic shell projection is a half-plane and at the boundary concentrated forces and moments are applied, is solved in the explicit form. This solution contains as particular cases the well-known solutions of the classical Flamant and Carothers problems.

Geometry, dynamics and fractals

10863
Tue·14:05·D

Marcelo Barros,† Augusto Galeão and Luiz Bevilacqua
National Laboratory for Scientific Computing, Brazil†

Consider a set of spring-mass oscillators. The springs are wires bent as to conform the geometry of each term of a fractal sequence (Koch triadic for instance) carrying a mass at one end. It is shown that the oscillation periods, for a given B.C., relate according to a power law with respect to a spring characteristic length whose exponent is $\alpha(\beta - D)$, β and α depend on geometry, material properties and BC and D is the fractal dimension of the sequence. Suppose now it is given a prime curve. If the first order approximation of the oscillator's periods built up with wire springs matching a sequence of samples cut off successively from the prime curve is a power law function, then the prime curve is a term of a fractal sequence. The power law approximation is function of the spring length—not wire length—or the volume encapsulating the spring—for space curves. This approach identifies randomness and can be coupled to physical experiments.

Axisymmetric solution for a tetragonal medium

10988
Tue·14:10·D

Marc Dahan
Université de Franche-Comté, France

An exact three-dimensionnal analysis is developped for an axisymmetric loading on the surface of a half-space composed by an anisotropic tetragonal (7 elastic coeff.) medium. The loading is assumed to be parallel to the elastic symmetry axis of the material. The general solution of the axisymmetric problem for a homogeneous medium is given for a surface concentrated loading by exact integral expressions, and from it a closed form solution for a point force is deduced. The numerical results are performed to show the anisotropic effect with isovalue curves of stress.

Influence functions and integral formulae for spherical thermoelastic bodies

10967
Tue·14:15·D

Seremet Victor,† Guy Bonnet and Tatiana Speianu
Agrarian State University of Moldova, Moldova†

This work proposes a new method to derive the influence functions for volume dilatation and Green's matrices for canonical domains of spherical system of coordinates. On this basis new thermo elastic influence functions and general integral formulae for determination of displacements in the cases of some classes of locally mixed boundary value problems in static and dynamical uncoupled thermo elasticity are suggested. The advantage of proposed formulae is that they allow us to unite the two-stage process of solving the boundary value problems in the theory of thermal stresses into one single stage. The desired thermo elastic displacements are determined directly via prescribed inner and boundary heat actions. An example of influence functions for displacements and integral solution of a mixed boundary value problem for thermo elastic wedge is considered.

Multi-field modelling of short wavelength deformations for Cosserat solids

10926
Tue·14:20·D

Andrey Miroshnichenko† and Aleksey Vasiliev
Australian National University, Australia†

We propose the method and derive the hierarchical system of multi-field models, which describe the dynamical properties of Cosserat lattice with an increasing accuracy. The N-field model is obtained as a continuum analogue for the discrete model constructed for a macro-cell containing N elementary cells by using N vector fields to describe the deformation of the lattice. Higher-order multi-field micropolar models are constructed by taking into account higher-order gradient terms. By comparison of the dispersion relations, we show that the multi-field generalisations are valid not only for long but also for short waves. We demonstrate that the multi-field model makes it possible to obtain localised rapidly varying static deformations, which are not reproduced in the frame of the single-field model.

Elastic fields in quantum dot structures with arbitrary shapes and interface effects

11069
Tue·14:25·D

Jianxiang Wang,† Haijian Chu, Huiling Duan and Bhushan Karihaloo
Peking University, China†

Elastic fields in quantum dot (QD) structures not only affect their physical and mechanical properties, such as optical and piezoelectric properties, degeneration and mechanical stability, but also play a significant role in their fabrication. These fields are induced by mismatches in the coefficients of thermal expansion and the lattice constants of species, and by external loading. In this paper we will present a general approach to the calculation of the elastic fields in QD structures of arbitrary shape. It can also deal with the anisotropy of the QD material, the non-uniformity of its composition of the QD, and the mismatch in the elastic constants of the matrix and the QD. This approach generalizes the Eshelby formalism to arbitrarily shaped anisotropic nano-inhomogeneities.

Size effect on probability of quasibrittle failure and lifetime: from atomistic to structural scale

11525
Tue·14:30·D

Sze-Dai Pang,† Jia-Liang Le and Zdeněk Bažant
National University of Singapore, Singapore†

The problem of rational determination of safety factors and prediction of lifetime for quasibrittle structures of various sizes is analyzed and the challenges are discussed. The paramount importance of reliability analysis is obvious if one notes that the load and understrength factors, still essentially empirical and physically poorly understood, represent much larger corrections to deterministic calculations than the typical errors of modern computer analysis of structures. When dealing with perfectly ductile or perfectly brittle materials, the proper cdfs of the nominal strength of structure are known to be either Gaussian or Weibull, respectively, and the type of cdf does not change with structure size and geometry. However, for quasibrittle materials, many of which came recently to the forefront of attention, the type of cdf has been shown to depend on the structure size and geometry. It is also shown that, in quasibrittle structures, there is strong size effect on the lifetime.

GILD mechanical field modeling

11665
Tue·14:35·D

Feng Xie,† Ganquan Xie, Lee Xie and Jianhua Li
Geophysical Laboratory, USA†

Many mechanical and physical problems can be reduced to study solution of PDE on a complicate inhomogeneous domain, which is embedded in an infinite homogeneous domain. To handle these problems, previous methods such as FEM and FDM meet serious difficulties. Advanced Global Integral and Local Differential (AGILD) mechanical modeling is presented to overcome these difficulties. The mechanical field differential integral equation in the boundary layered strip zone is derived. The mechanical Galerkin equation in the internal domain is used. The differential integral equation and Galerkin equation are coupled to construct AGILD mechanical modeling. The inversion of the Galerkin FEM matrix equation is assumed piecewise successively. The AGILD mechanical modeling is accurate and fast. The AGILD modeling is useful for analyzing complicate structure and for investigating nanometer materials and for making virtual visualization of the computational movie, for example, computer game.

Intrinsic field tensors for strongly orthotropic continua

11677
Tue·14:40·D

David Kellermann,† Tomonari Furukawa and Don Kelly
University of New South Wales, Australia†

This work presents a general case for usage of intrinsic field tensors; these overcome the erroneous kinematics and finite strains resulting from deformation of strongly orthotropic continua as described by symmetric Lagrangian strain tensors. This includes the Green, Biot and infinitesimal Cauchy strain. The latter of these is referred to as the isotropic linear strain tensor because, according to asserted theory, its symmetry is derived from an assumption of isotropic material properties. Considering these strain metrics were originally derived specifically for isotropic media, the validity of an orthotropic linear strain tensor leads to the proposition of a class of intrinsic field tensors that can generalize any existing Lagrangian strain tensor along with their specialized counterparts such as the structural tensors. Pursuant to this, we develop the equivalent orthotropic intrinsic field formulation for the infinitesimal Cauchy, the Biot and the Green strain tensors.

Stress analysis of curved elastic bar and elastic wedge under bending load

11761
Tue·14:45·D

Vyacheslav Lyakh
Kiev National Taras Shevchenko University, Ukraine

This work addresses an analytical solution of two boundary-value problems of plane elasticity concerning bending/torsion of a curved elastic bar and a truncated elastic wedge. Method of superposition is introduced. Proceeding from asymptotical analysis, improved reduction method is applied to infinite systems of algebraic/integro-algebraic equations derived. Mechanical conclusions are original and significant. The solution on a curved bar shows that corresponding results by Timoshenko and his using Saint-Venant's principle as regards closed bodies should be considerably refined for some domains' sizes. As to an infinite wedge, the exact solution for arbitrary wedge angle and boundary conditions on a circular boundary was obtained. The strict connection with the method of homogeneous solutions is derived. For a moment-replacement loading the expansion by homogeneous solutions appearers to be in complete agreement with results by Sternberg and Koiter.

Mechanics of nonlinear acoustoelasticity in fluid-saturated porous rocks

10590
Tue·14:50·D

Jing Ba,[†] Jiong Liu, Huizhu Yang, Liyun Fu and Mengqiu Guo
Tsinghua University, China[†]

Based on the semilinear and nonlinear Biot theory, a unified treatment of the mechanics of nonlinear acoustoelasticity of finitely deformed porous rocks is presented. We derive the wave equations from the 11-constant hyperelastic potential function in fluid-saturated porous media, by introducing finite strain into Biot theory and substituting the potential functions into poroelasticity motion governing equations. This particular approach provides a theoretical way to describe the solid-fluid coupling phenomena in highly compressed fluid-saturated porous solid. Analyzing the oscillatory friction force between the pore fluid and the solid matrix, quantitative relationships of P- and S-waves' velocities versus hydrostatic pressure are obtained in higher frequency ranges. The theory of nonlinear acoustic propagation is extended to include two-phase, Biot diffusion and finite deformation.

Analytical mechanics of bars, plates and shells on asymmetrical theory of elasticity

10679
Tue·14:55·D

Samvel Sargsyan
Gyumri State Pedagogical Institute, Armenia

In present work the unique asymptotic method of constructing the general applied static and dynamic theories for thin homogeneous and multilayered micropolar elastic bars, plates and shells is constructed. A unique asymptotic method is developed and on the basis of the asymmetrical (momental, micropolar) theory of elasticity there are constructed one-dimensional and two-dimensional models for homogeneous and layered bars, plates and shells with free and constraint rotation. These models are built with the help of inner and outer (boundary layer) asymptotic expansion with the study of their interaction, depending on the values of physical sizeless parameters. On the basis of the constructed general applied theories of micropolar thin bodies, a number of dynamic and static problems of homogeneous and multilayered bars, of rectangular, round plates and of cylindrical shells are studied.

A multiscale projection method for fracturing solids in three dimensions **11378** Tue·16:00·B

Stefan Loehnert,† Dana Mueller-Hoeppe and Peter Wriggers
Leibniz Universität Hannover, Germany†

We present an efficient multiscale projection method for the calculation of macrocracks interacting with microcracks. The method is based on the extended finite element method (XFEM) used on all scales, which allows for an accurate simulation of arbitrary fracture processes in two and three dimension. In this contribution an emphasis is set on the transition of the field variables between the different scales. We compare the results to analytical solutions obtained for a variety of examples.

Variational treatment of crack problems in plane micropolar elasticity **10649** Tue·16:20·B

Stanislav Potapenko
University of Waterloo, Canada

In this presentation we use the boundary-integral equation method to obtain the solution for stress concentrations around a crack in plane micropolar elasticity. The corresponding boundary-value problem is formulated in Sobolev space setting and the corresponding analytical (weak) solution is found in terms of the modified integral potential. We consider an example of a crack in a human bone which is modelled under assumptions of plane micropolar elasticity and demonstrate the effectiveness of the suggested approach.

Two-dimensional thermoelasticity problems for a rectangle **11000** Tue·16:40·B

Yuriy Tokovyy,† Chien-Ching Ma and Viatcheslav Meleshko
National Taiwan University, Taiwan†

The talk addresses the various analytical methods for the classical two-dimensional biharmonic problem for a rectangular region. A short historical survey of the early stages of the method of homogeneous solutions is presented. An rather unknown algorithm suggested by P.F. Papkovich (1940) for the solution of this problem is discussed with the spotlight fixed on treatment of plane elasticity and thermoelasticity problems for a rectangle. The algorithm is illustrated by typical examples. Comparison of computed results with ones established by means of the method of superposition show an excellent agreement. The advantages and disadvantages of the algorithm are emphasized.

On the mechanical analysis of plates composed of functionally graded material **10195** Tue·17:00·B

Holm Altenbach† and Victor Eremeev
Martin-Luther-Universität Halle-Wittenberg, Germany†

A new plate theory based on the direct approach is introduced and applied to plates composed of functionally graded materials (FGM). The governing equations are formulated for a deformable surface, the stiffness parameters are identified for the case of linear-elastic isotropic material behavior. The material properties are changing in the thickness direction. Solving some problems of the global mechanical analysis it will be demonstrated that in some cases the results significantly differ from results based on the Kirchhoff-type theory. The considered approach to model FGM plates within the framework of a 5-parametric theory of plates has an advantage with respect to theories of sandwich or laminated plates. Further investigations should be directed on the thermomechanical behavior if FGM plates.

Time dependent mechanical response of the cell cytoskeleton

11663
Tue·17:20·B

Robert McMeeking,† Anthony Evans, Vikram Deshpande, Zhensong Wei and Amit Pathak
University of California, Santa Barbara, CA, USA, USA†

A model for the time dependent mechanical response of the cytoskeleton of biological cells is presented. It is motivated by 3 key bio-chemical processes: (i) an activation signal that triggers actin-myosin motors, (ii) the tension dependent assembly of the actin and myosin into stress fibers and (iii) the crossbridge cycling between the actin and myosin filaments that generates the tension. The outcome of the model is a nonlinear viscoplastic response with special features that characterize the cell biochemistry. Simulations that incorporate this model have been used to rationalize the following observations. Uniaxial cyclic stretching of cells causes stress fibers to align perpendicular to the stretch direction, with the degree of fiber alignment dependent on the loading frequency, reflecting the creep characteristics of the model. Stress fiber alignment increases with increasing cycling frequency. The results presented confirm that the model reproduces many experimental observations.

The role of fiberwise constraints in the mechanics of linearly elastic shells

10989
Thu·09:15·4

Paolo Podio-Guidugli
University of Rome Tor Vergata, Italy

It is shown what fiberwise constraint involving the first displacement gradient is expedient to capture the structure thinness peculiar of linearly elastic shell-like bodies capable of shearing deformations.

Finite-amplitude Love waves in a pre-stressed neo-Hookean material

11110
Thu·09:35·4

Elizabete Ferreira,† Philippe Boulanger and Michel Destrade
Universite Libre de Bruxelles, Belgium†

In the context of the non-linear elasticity theory we consider a model for compressible solids called “compressible neo-Hookean material”. We show how finite-amplitude inhomogeneous plane wave solutions and finite-amplitude unattenuated solutions can combine to form a finite-amplitude Love wave. We consider a layer of finite thickness overlying a solid half-space, both made of different pre-stressed compressible neo-Hookean materials. We derive an exact solution of the equations of motion and boundary conditions. We obtain an explicit dispersion equation similar to that of the linear case, but the scope of the results is now richer because they include large amplitude and pre-stress. Also, we investigate the special case when the interface between the layer and the substrate is in a principal plane of the pre-stress, showing the effects of the strain-induced anisotropy on the wave characteristics. Results for the energy flux and the energy density of the waves are also presented.

Effect of cubic elasticity on the distribution of stress in polycrystals

11392
Thu·09:55·4

Maxime Sauzay
Commissariat à l’Énergie Atomique, France

Plasticity mechanisms are usually discussed based on the Schmid factor distribution, neglecting the anisotropy of cubic elasticity. To evaluate its effect on the distribution of resolved shear stress, many FE computations are carried out using meshes of multicrystals and random crystalline orientations. Many materials are considered, exhibiting the whole range of anisotropy factor value, a, from the lowest (RbI, $a = 0.26$) to the highest (Lithium, $a = 9.1$). For Cubic Face Centred metals and $a > 1$, the shear stress distribution is shifted towards lower values. It is noticeable even for usual metals. The distribution computed for copper allows a more accurate prediction of the fraction of plastically-deformed grains than the Schmid factor distribution. The orientations of its neighbour grains are as influent as of the orientation of the grain itself. It explains the variability in the dislocation structure among grains with the same orientation often reported in the literature.

On variational formulations for nonlocal elasticity

10294
Thu·10:15·4

Francesco de Sciarra
Universita' di Napoli Federico II, Italy

One of the main drawbacks of local elasticity consists in the fact that many problems, such as sharp crack-tip in continuum fracture mechanics, lead to stress singularities in classical elastic theories. In the present paper, starting from the nonlocal elastic constitutive model proposed by Eringen and co-workers, the thermodynamic framework and the boundary-value problem for nonlocal elasticity are formulated and the complete set of nonlocal mixed variational principles is then provided. A recently proposed symmetric spatial weight function which preserves constant fields is considered. A firm variational basis to the nonlocal model is provided and ten admissible combinations of the state variables are allowed. A discussion on uniqueness of the solution of the nonlocal model is provided. The variational formulations for nonlocal linear elasticity presented in literature, following an ad hoc reasoning, are then recovered. A consistent symmetric nonlocal FE procedure is then derived.

The definition of the displacement function by the elements of Cauchy's tensor

10825
Thu·14:00·C

Turatbek Duishenaliev
Kyrgyz State Technical University, Kyrgyzstan

Vector field can be defined by its divergence and rotor. This field can be represented as a sum of irrotational field and solenoidal field. The finding of such field leads to the solution of the partial differential equations at some boundary conditions. The solution of static boundary problem in stress gives the field for stress tensor, from which we can define the field of linear Cauchy's deformation tensor. Problem of finding the displacement field, corresponding with the deformation tensor, arises. In this work the development of Cesaro's formula is set in. Cesaro's formula was almost unused because of the laboriousness of the integration. In this work the program is developed in the system MathCAD, which firstly checks the satisfaction of the equations of compatibility of deformations, and then quite successfully carries out this integration in character form.

New model for piezoelectric medium with initial porosity and analysis of ultrasonic piezoelectric devices

11819
Thu·14:05·C

Andrey Nasedkin
Southern Federal University, Russia

For modelling piezoelectric materials the new mathematical model is suggested, which generalize the model of the electroelastic medium with damping properties and the Cowin–Nunziato model of the elastic medium with voids. The formulations of the boundary value problems for piezoelectric bodies with voids are formulated, and the generalized statements are obtained in the expanded and reduced forms. Finite element approximations of the problems for piezoelectric bodies with voids are also given in the expanded and reduced forms. Mathematical properties of the natural frequencies and eigenvectors are investigated in details for different types of the boundary conditions. Using this model for piezoelectric bodies with voids, the effective moduli of porous piezoceramics are defined

more precisely. The efficiency of the proposed model is illustrated by the example of the analysis of a focusing spherical device from porous piezoceramics emitting ultrasonic waves in the acoustic medium.

Continuum dislocation theory and size effect

11844
Thu·14:10·C

Khanh Le
Ruhr-Universität Bochum, Germany

Within the framework of continuum dislocation theory the plane constrained shear of single and bicrystals is investigated. Analytical solutions are obtained for single and symmetric double slip. All solutions exhibits an energetic and dissipative threshold for the dislocation nucleation, the Bauschinger translational work hardening and the size effect.

Notes on stresses in chains

12051
Thu·14:15·C

Marcelo Epstein† and Reuven Segev
University of Calgary, Canada†

This work presents a generalization of the theory of stresses and equilibrium that is based on Whitney's geometric integration theory. As such it is concerned with the following issues: the class of admissible domains, the existence of stresses and the class of admissible stress fields, integration theory, and Green–Gauss–Stokes theorem. Stresses are defined as elements of the dual of a space of virtual displacements. This implies that the regularity of stresses is controlled by the assumed regularity of the virtual velocities in an optimal way. The theory allows regions which are quite irregular, for example, various fractal sets for which the boundary area is infinite and the normal vector is not defined at any point on the boundary. This work extends an earlier one by considering stresses rather than flux fields and by presenting the balance equation, written in terms of vector cochains, as a generalization of the principle of virtual work.

Green's function for plane anisotropic elastic bimaterials with imperfect interface

11173
Thu·14:20·C

Leszek Sudak
University of Calgary, Canada

In this talk, a rigorous solution for the two-dimensional Green's function in an anisotropic elastic bimaterial is presented. Most significant is the fact that the bonding along the bimaterial interface is considered to be homogeneous imperfect. Using complex variable techniques the basic boundary value problem for two analytic vector functions is reduced to a coupled linear first-order differential equation for a single analytic vector function defined in the lower half space. The coupled linear differential equation for the single analytic vector function can be subsequently decoupled into three independent linear first-order differential equations for three newly defined analytic functions. Closed-form solutions for the two-dimensional Green's function are subsequently derived. The key feature of the present method is that the physical quantities can be readily calculated without the need to perform any inverse transform operations.

Continuum modeling of elastic dielectric solids with defects, with application to barium strontium titanate thin films

10502
Fri·09:15·4

John Clayton,† William Nothwang, Michael Grinfeld and Peter Chung
United States Army Research Laboratory, USA†

A model is developed for the electromechanical behaviour of dielectric crystals with point, line, and surface defects. A geometric framework describes deformation of the lattice. Thermodynamic and kinetic relations are formulated, the latter enabling description of diffusion of charged vacancies and mass rearrangement at free surfaces. Numerical and analytical solutions offer insight into performance of barium strontium titanate (BST) thin films above the Curie point. In one spatial dimension and under the action of an external voltage, the transient numerical solution demonstrates how vacancies coalesce into layers of large concentration near shorted electrodes, leading to an increase in the electric field in the vicinity of such boundaries that may affect loss characteristics of the film. Heterogeneous surface growth of the film resulting from small initial perturbations is evident in 3D numerical solutions.

Mathematical modeling of linearly piezoelectric slender rods

11034
Fri·09:35·4

Thibaut Weller† and Christian Licht
Centre National de la Recherche Scientifique, France†

The mathematical modeling of elastic thin plates or slender rods through asymptotic analysis has become classical: the thickness or the diameter is assigned to a role of parameter whose aim is to tend to zero. We have extended this method to linear piezoelectric and electromagneto-elastic plates. But, because beam modeling requires to condense on a line the properties of slender 3D objects having one dimension prevailing on the others, it is more challenging than plate modeling. Depending on the boundary conditions, two limit models, corresponding to sensors or actuators, appear. They involve a greater number of state variables than the couple (displacement/electrical potential) of the genuine 3D physical problem. We therefore exhibit reduced formulations where the number of variables drops to one or two, one reduced problem being purely mechanical! We discuss the conditions for which the elimination of additional variables leads to nonstandard equations involving nonlocal terms.

Internal variables and microstructured materials

11079
Fri·09:55·4

Juri Engelbrecht,† Arkadi Berezovski and Gerard Maugin
Tallinn University of Technology, Estonia†

Internal variables are used for the description of microstructure in continuous media for decades. However, their usage is limited commonly to dissipative processes. The non-dissipative processes are associated with internal degrees of freedom. Recent developments in the internal variable theory allow us to propose a unified framework for the description of both dissipative and non-dissipative processes under one umbrella and to clarify the structure of generalized continuum theories on the basis of the canonical thermomechanics on the material manifold including weakly non-local dual internal variables enriched by an extra entropy flux. This formalism includes both dissipative reaction-diffusion equations and second grade and second gradient theories. As it is demonstrated, the Mindlin micromorphic theory can be represented in terms of dual internal variables in a natural way in the framework of canonical thermomechanics.

Analysis of interfacial crack by means of hypersingular integro-differential equations

11350
Fri·10:15·4

Noda Nao-Aki
Kyushu Institute of Technology, Japan

Numerical solutions of hypersingular integro-differential equations are discussed in the analysis of interfacial crack in two and three dimensional bimaterials subjected to general internal pressure. The problem is formulated on the basis of the body force method. In the numerical analysis, unknown body force densities are approximated by the products of the fundamental density functions and power series, where the fundamental density functions are chosen to express singular behavior along the crack front of the interface crack exactly. The present method gives rapidly converging numerical results and highly satisfied boundary conditions throughout the crack boundary. The stress intensity factors are given with varying the material combination and aspect ratio of the crack. It is found that the stress intensity factors and are determined by the bimaterials constant alone, independent of elastic modulus ratio and Poisson's ratio.

SM06 :: Experimental methods in solid mechanics

Chairs: Jacques Desrues (France) and Julia Greer (USA)

Mon	14:00–16:00	Hall E	Lectures
Mon	16:25–17:45	Hall E	Lectures
Tue	14:00–14:30	Room 2	Seminars
Fri	11:00–11:20	Room 5	Lectures

The effect of vibration, amplitude of vibration, roughness, and speed on the coefficient of friction of metals

11638
Mon·14:00·E

Jamil Abdo,† Suliman Al-Salmi, Hashel Al-Naabi and Nasra Al-Maskari
Southern Illinois University, USA†

Experiments were conducted to determine the effect of vibration, amplitude of vibration, surface roughness, and sliding speed on coefficient of friction (CoF) of different metals. A pin-on-disc apparatus was constructed and design of experiments technique is introduced to determine the effect of different levels of the factors and their cross influence on CoF. The design is performed using response surface method (RSM). The CoF is analyzed as a nonlinear function of the factors. Results suggested that the presence of vibration and amplitude of vibration affect the CoF considerably. The values of CoF are non-linearly decreased with the increase of the vibration and the amplitude of vibration. The values of CoF decrease almost linearly with relative speed at all levels of vibration. The values of CoF of Aluminum alloy disc are linearly increased with the increases of the roughness but they are slightly increased when the Stainless Steel disc is used.

Recent developments and applications of the ISSR technique

11048
Mon·14:20·E

Keyu Li
Oakland University, USA

The article reviews the recent developments and applications of the interferometric strain/slope rosette (ISSR) technique. The ISSR is a laser-based technique to measured three strains and three slopes on material surface over gage lengths on order of 100 micrometres. The ISSR has been recently developed into multiple ISSR (multi-ISSR) with more capability of measuring deformation and rigid-body motion. The ISSR technique in conjunction with either hole-drilling or ring-core cutting method is developed to measure residual stresses at localized areas. The techniques are unique to measure high stress gradients and stress concentrations. As the ISSR gage length is comparable to size of finite element, the ISSR technique is being applied to evaluate material constitutive models and finite element simulation to study residual stress problems in industries to aid design of structure and manufacturing processes.

Measurements of discontinuous displacement fields by extended 3D image correlation using X-ray tomography

10336
Mon·14:40·E

Francois Hild,† Stéphane Roux, Julien Réthoré, Jean-Yves Buffière and Jean-Philippe Tinnes
LMT-Cachan, France†

The present paper aims at showing 3D measurements of displacement fields in cracked samples made of nodular graphite cast iron. X-RAY computed microtomography is used to obtain 3D images of the sample under different loadings. An extension of digital image correlation to three dimensional

images is proposed using a global approach and a finite element description of the displacement field, including crack discontinuity enrichments (similar to the extended finite element method). The proposed technique allows for the quantification of displacement jumps over the entire detected crack surface in a fatigue experiment.

In-situ investigation of nano-scale plasticity in FCC and BCC crystals via homogeneous deformation of nano-pillars

10545
Mon·15:00·E

Julia Greer,† Steffen Brinckmann and Ju-Young Kim
California Institute of Technology, USA†

Strength of crystals is important in device reliability. Flow stress is found to strongly depend on sample size at nanoscale. To investigate plasticity under homogeneous deformation we developed micro-deformation methodology where nanopillars fabricated by Focused Ion Beam are uniaxially deformed and stress versus strain relationship is obtained. Plastic flow stress increases according to power law as pillar diameter is decreased demonstrating that size effect exists even without strain gradients present in bending and indentation experiments. To visualize deformation we built a new instrument with in-situ tension and compression capabilities, which measures mechanical response of nanoscale materials while capturing video. We present results of in-situ deformation tests and report mechanical strengths of pristine and oxide-coated FCC nanopillars and compare them to BCC. All crystals show increase in flow stress with decreasing diameter in power-law fashion, but with different slopes.

Characterization of the stress–strain relationships of ductile films using sharp indentation

11940
Mon·15:20·E

Yyongli Huang,† Yanguo Liao and Yichun Zhou
Xiangtan University, China†

Using dimensional analysis and finite element computation, a new set of dimensionless analytical functions were constructed to relate the indentation data to elastic-plastic properties of ductile film/ductile substrate system, thus the forward and reverse analysis were established. With the reverse analysis and indentation tests, the Young's modulus, yield strength and work hardening exponent were gained for nickel films electrodeposited on mild steel substrate. The results indicate that the Young's modulus and yield strength of nickel films are both higher than those of nickel bulk materials, and increase while the thickness of films decrease, but the work hardening exponent will decrease with the decrease of film thickness.

Evaluation of whole-field thin-film stress and strain by the biharmonic function

11157
Mon·15:40·E

Wei-Chung Wang,† Kai-Hung Cheng and Chi-Hung Hwang
National Tsing Hua University, Taiwan†

In this paper, a new whole-field method for calculating intrinsic stress of optical thin film is proposed. A Zygo interferometer was used to measure surface contours of circular glass plates before and after SiO_2 film deposited. Using the Zernike polynomial fitting algorithm, surface contours before and after deposition was generated from the polynomial coefficients to visualize the deformation. The Zernike polynomials are assumed to be functions of both optical characteristics and mechanical displacement. During depositing the thin film, there is no external force applied on the glass plate and thin film. Therefore, the function of mechanical displacement must satisfy the biharmonic function. The strain in the thin film can then be obtained by differentiating the resulting polynomials. In addition, the curvature and shear strain distributions calculated by the fitted Zernike polynomial indicate that the possible failure location is near the edge of the glass plates.

Mechanical characterization of materials by micro-indentation and AFM scanning

10066
Mon·16:25·E

Gabriella Bolzon,† Enzo Chiarullo and Massimiliano Bocciarelli
Politecnico di Milano, Italy†

Instrumented indentation test represents a practical methodology for the calibration of parameters entering constitutive models, widely used in industries dealing with micro and nano technology and with thin coatings for a large and still growing number of applications. Recent research results have shown that geometrical data concerning the residual imprint generated by indentation of elastic-plastic materials constitute an important experimental information, supplementary to the usual one consisting of the load versus penetration curves, to be exploited for parameter identification purposes. This communication is intended to illustrate the benefits of AFM scanning, possibly coupled with digital image correlation techniques, in these inverse analysis procedures for the mechanical characterization of materials.

Determination energy dissipation for aluminium deformed dynamically at modified Taylor impact test

10953
Mon·16:45·E

Leopold Kruszka
Military University of Technology, Poland

The paper presents the methodology and results pertaining to the thermomechanical behavior of the aluminium A1 (Polish standard) loaded in compression at high strain rates of 102–103 s^{-1} during the modified Taylor impact test. Specifically, I use the thermovision set to record the evolution of the surface temperature in specimens with different lengths and adequately devised procedure to determine the fraction of plastic deformation work converted to heat with strain and strain rate, based on experimental stress-strain-strain rate dependencies. The point of view adopted here is purely phenomenological as no attempt is made to provide an underlying micromechanical model for the observed results.

3D volumetric DIC of X-ray microtomographic images to study localized deformation in a stiff clayey rock

10659
Mon·17:05·E

Jacques Desrues,† Michel Bornert, Pierre Besuelle, Gioacchino Viggiani and Nicolas Lenoir
Grenoble University, France†

The technique of X-ray computed tomography allows non destructive imaging and quantification of internal features of bulk objects. Within the framework of feasibility studies of underground repositories for radioactive waste, the study of the permeability evolution of the host layer induced by fracturation in the Excavation Damaged Zone (EDZ) around the galleries requires accurate experimental information on the mechanisms of localized deformation and crack formation under mechanical loading. An original loading device has been developed to be used with X-ray micro tomography on a synchrotron beamline at ESRF, France. A set of triaxial compression tests using this advanced experimental set-up have been performed on specimens sampled from borehole cores. This paper illustrates the results obtained, with a special focus on the major advances resulting from the combination of X-Ray CT imaging and 3D volumetric Digital Image Correlation.

A new method for characterizing the surface periodic structure of photonic crystal and its application

10942
Mon·17:25·E

Huimin Xie,† Fulong Dai, Satoshi Kishimoto and Qinghua Wang
Tsinghua University, China†

Integrated inversion idea with Laser Scanning Confocal Microscopy (LSCM) Moiré method, LSCM Moiré inversion method is proposed to characterize the surface periodic structure of photonic crystal class. This method possesses the advantages of both LSCM and Moiré method, and is a nonlocal, economical, and nondestructive measuring method for photonic crystal class structure. The shape feature of the surface periodic structure in several hundreds of millimeter, as well as the dimension at micro- and nano-scale, can be obtained through seeking the specimen grating equation as well as virtual strain distribution. Principle of LSCM Moiré inversion method is introduced. Its application in characterizing the surface structure of a Japanese cabbage butterfly wing indicates there are curve gratings with a little less than 438 nm pitches on the scales, which provides the possibility for further explaining its attractive iridescence.

The research of measuring polymerization shrinkage of composite resins with ESPI

10662
Tue·14:00·2

Guobiao Yang† and Zhang Zhang
Tongji University, China†

In this study, the method of electronic speckle pattern interferome (ESPI) was used to measure polymerization shrinkage of composite resins. The ESPI apparatus was constructed to measured the out-of-plane displacement of the resins surface during the polymerization. Experiments demonstrated that ESPI technique was a viable method to measure the deformation of composite resins. It was responsive and sensitive to size. Cavity shape, size influenced the date of resins shrinkage. The tooth deformation in response to polymerization of resins was measured by ESPI. It is a feasible method for assessing resins deformation induced by its polymerization shrinkage when it was bonded in tooth cavities. The results were greatly influenced by the dimensions of cavities, or interface adhesive and soon. It could also measure the tooth deformation induced by shrinkage of bonded composite resins. Resins polymerization shrinkage date may overestimate shrinkage induced tooth deformation.

Development of an automated load and measurement device

10714
Tue·14:05·2

Mohsen Javadi† and Bernd Behrens
Institute of Metal Forming and Metal-Forming Machines, Germany†

This contribution deals with an innovative load and measurement system to extend the static characterization of metal-forming machines. For this purpose, an automated load and measurement device (LMD) has been developed and built, whereby the determination the other factors like warming up influences is provided. The LMD can be used for presses with a nominal force between 1,600 and 6,000 kN. Using this device the manual time-consuming procedure according to the DIN 55189 can be replaced by an automatic procedure which decreases the necessary time for the investigation of a press from several hours to about 45 minutes. Due to the automation of the measuring procedure it is possible for press users to get an overview of the actual condition of a press and the wear history in ram slide ways by using the device frequently. The application of the LMD increases in addition the reproducibility of the results.

The optoelectronic method for measurement of small dynamic displacements

10740
Tue·14:10·2

Michael Osipov,† Lydia Osipova and Maxim Popov
Samara State University, Russia†

The optical methods have a number of advantages in comparison with other methods—mechanical and electrical methods. The optical methods, as a rule, are non-contact gauges. The contact gauges, used for research of dynamic processes, essentially influence the characteristics of this phenomenon. It is very difficult to determine their own dynamic characteristics that can result in significant errors at measurements. The developed laser interferometry for measurements of the small dynamic displacements is discussed. The optoelectronic method of the signal registration from laser interferometer and the method of the signal processing are presented. This technique allows us to determine the amount and form of the dynamic displacements with high sensitivity and accuracy. The developed Michelson's interferometer has the following parameters: a range of registered frequencies from 0 Hz up to 10^8 Hz; the sensitivity and accuracy of the measurements of an amplitude of vibrations makes ± 3 nm.

Acoustic emission detection for damage evaluation of thermal barrier coatings under cyclic heating

11725
Tue·14:15·2

Li Yang,† Yichun Zhou, Weiguo Mao and Qixing Liu
Xiangtan University, China†

The acoustic emission (AE) detection of ZrO_2-8% wt.% Y_2O_3 (YSZ) thermal barrier coatings (TBCs) during the whole cyclic heating process has been successfully conducted using a Platinum waveguide. AE parameters including event count, amplitude and frequency spectrum, Scanning electron microscopy (SEM), and stress state in TBCs during cyclic process were analyzed for information regarding the fracture behavior of TBCs. The experimental results showed that the rapid increase of the AE signals in the cooling stage with higher amplitudes indicated the occurrence of serious damages such as delamination and spallation. AE results also showed that the damage in the TBCs occur in both cooling and heating stages of the cycling. Such failure feature was well expressed by the stress evolution in TBCs during cyclic heating.

A lattice unit model to evaluate interfacial residual stress in ferroelectric thin film

10966
Tue·14:20·2

Xuejun Zheng,† Yichun Zhou and Qingyong Wu
Xiangtan University, China†

Under macro-mechanics frame to measure residual stress, the inherent electromechanical coupling, polycrystalline orientation and substrate effect were not considered, and the interfacial residual stress in ferroelectric thin films were not evaluated with the conventional method based on X-ray diffraction. We propose a lattice unit model to evaluate the interfacial residual stress. Using this model, the in-plane residual stresses in $Pb(Zr0.52Ti0.48)O_3$ thin films prepared by two different methods were evaluated by the decline parameter of film thickness. The results show that the surface residual stress is good consistency with that evaluated by the previous models. The interfacial residual stress effects on film fracture are discussed.

A novel magnetostrictive acoustic transducer for longitudinal guided wave inspection of steel strands

11449
Tue·14:25·2

Zenghua Liu,† Bin Wu, Su Liu, Cunfu He and Yinong Zhang
Beijing University of Technology, China†

The development of a magnetostrictive acoustic transducer for generating and receiving longitudinal guided waves in seven-wire steel strands is described in this paper. The sensitive part of this transducer consists of a three-section spiral tube and coils wound around the spiral with reverse normal winding directions along the axis direction of steel strand. For reducing the effect of magnetic resistance in air to magnetic circuit, a group of thin clips which inner shape is transverse cross section of steel strand and outer shape is circular. Three permanent magnetic are installed outside of thin circle clips uniformly for providing homogeneous magnetic field inside of the spiral tube and steel strand. It is shown that the transducer is capable of generating and receiving the wanted $L(0,1)$ mode in steel strands. Furthermore, an artificial notch in a helical wire of steel strand can be detected using this novel acoustic transducer.

Measuring deformation of large vessels with innovative broken-ray videometrics

10984
Fri·11:00·5

Yu Qifeng,† Fu Sihua, Jiang Guangwen and Shang Yang
National University of Defense Technology, China†

An innovative broken-ray videometrics method is proposed to resolve the problem of ship's deformation measurement which is a difficult task and highly concerned in the ship industry. For a large structure of ship, the traditional deformation measurement techniques are not suitable for because they only measure local deformation. The broken-ray videometrics method can measure the pose, including the attitude angles and the position between the principal reference and non-intervisible target due to the intricate structure or devices of large vessels. Broken-ray path is constructed by relay-stations, each of which consists of cameras and/or markers. By processing the images sequence, the real-time dynamic ship deformation can be measured and the errors caused by the deformation for the ship can be compensated. Finally, laboratory experiment is designed and implemented which shows satisfactory accuracy.

SM07 :: Fracture and crack mechanics

Chairs: Dietmar Gross (Germany) and Robert Goldstein (Russia)

Tue	10:40–12:40	Room 1	Lectures
Tue	14:00–14:50	Room 1	Seminars
Tue	16:00–17:40	Room 1	Lectures
Wed	10:40–13:00	Room 1	Lectures
Thu	11:00–12:40	Room 3	Lectures

A predictive model for chipping wear of hard coatings **11651** Tue·10:40·1

Leon Keer† and Kun Zhou
Northwestern University, USA†

A two-dimensional model based on fatigue fracture is developed to explain and predict chipping wear of coatings under cyclic rolling/sliding contact. In the model, it is assumed that there are pre-existing micro-cracks within the coating. Depending on the stress field at the crack tips, such cracks can propagate in different directions under cyclic contact load. The numerical results have demonstrated that both tips of a crack may grow to reach the coating surface thus causing a particle to detach from the coating under certain circumstances. A few parameters have been found to be crucial to particle detachment, e.g., the depth of a pre-existing crack from the surface, the position of the crack relative to the major roughness asperities, the loading pattern, and the number of loading cycles. The model can be used to predict the range of the cycle numbers for particle detachment and the size scale of the detached particles.

Structural-kinetic approach in dynamics of continuum: fracture, spalling, cavitation, electrical breakdown **11646** Tue·11:00·1

Arseny Kashtanov† and Yuri Petrov
St Petersburg State University, Russia†

Experimental investigations of the dynamic fracture of solids (crack problems and spalling fracture), liquids, and electrical breakdown in insulators reveal the fundamental difference in the media response to the dynamic and static loading conditions. For all the physical processes considered here the common dynamic strength behavior is experimentally observed: the dynamic-strength diagram is characterized by two asymptotes corresponding to an extremely short and extremely long pulse loading durations. In the presented paper the unified approach to predict the dynamic strength of media is proposed based on the Morozov-Petrov's concept of incubation time. It operates with the function defining the "damage" level of material at the different stages of incubation process. It provides the detailed investigation of the preliminary stage of dynamic fracture (breakdown) as well as the statement of dynamic-strength criterion at the macroscale.

Dynamic fatigue behavior of cracked piezoelectric ceramics in three-point bending under electromechanical loading

11021
Tue·11:20·1

Yasuhide Shindo,† Fumio Narita and Mitsuru Hirama
Tohoku University, Japan†

In this study, we report theoretical and experimental examination of the dynamic fatigue crack growth in piezoelectric ceramics under electromechanical loading. A crack was created normal to the poling direction. Constant load-rate testing was conducted in three point flexure under zero and positive electric fields using single-edge precracked-beam method. A finite element analysis was also used to evaluate the energy release rate for the permeable, impermeable and open crack models, and the effect of electric field on the energy release rate was discussed. The results were then examined in terms of the crack propagation velocity vs energy release rate curve. It is found that the energy release rates predicted by the permeable and open crack models under practical loading conditions may not be significantly different. Also, the piezoelectric ceramics under positive electric field has lower dynamic fatigue crack growth resistance, compared to those under no electric field.

An extended Gurson model accounting for strain localization within thin planar layers

11334
Tue·11:40·1

Jean-Baptiste Leblond† and Gérard Mottet
Universite Pierre et Marie Curie, France†

Propagation of cracks in ductile materials occurs through coalescence of cavities and/or formation of shear bands. The classical Gurson–Tvergaard–Needleman (GTN) model incorporates some phenomenological modelling of coalescence, but not of formation of shear bands assisted by the presence of microvoids. This paper tries to solve the ensuing difficulties by proposing a unified model of both coalescence and formation of shear bands in porous plastic solids. Both phenomena are viewed as expressions of the same basic effect, strain localization within thin planar bands, at some "meso" scale. The principle of the approach consists of treating the heterogeneous medium as an idealized superposition of alternately sound and porous layers, in which the mechanical fields are considered as homogeneous. The model developed is applied to the numerical simulation of the "cup-cone" fracture of a smooth axisymmetric specimen, and is found to predict an easier localization than the standard GTN model.

Condition for crack deviation in an anisotropic solid and its dependence on a crack model

11472
Tue·12:00·1

Efim Shifrin† and Robert Goldstein
Institute for Problems in Mechanics RAS, Russia†

A problem for a straight mode I crack located on a symmetry axis of an orthotropic plane and subjected to biaxial tension is considered. Conditions for the crack deviation are studied. The strength properties of the solid are supposed to be isotropic. A crack is modeled by a thin elliptic cavity. It is supposed that the fracture propagates in the direction where maximal tensile stresses are attained. The directions of fracture propagation are determined. The directions depend on the length of the minor ellipse semiaxis. Considering the limit fracture direction when the length of the minor ellipse semiaxis tends to zero one obtains a crack propagation direction. A problem of a straight crack path stability is considered also using a thin elliptic cavity as a crack model. Condition of a straight crack path instability is obtained. This condition is compared with the condition following from the usual ideal cut crack model.

Analysis of notches and cracks in laminated plates by means of scaled boundary finite elements

11475
Tue·12:20·1

Jochen Hebel† and Wilfried Becker
Technische Universität Darmstadt, Germany†

A new scaled boundary finite element formulation for the static analysis of laminated plates is presented. Having been applied successfully to continuum mechanics problems, the method is extended to arbitrary laminated plates. Using scaled boundary coordinates, the problem is formulated in a discrete form of the Kantorovich reduction method with unknown displacement functions for the scaling direction and finite element discretisations for the other direction. By application of the principle of virtual work, the governing equations are derived. The resulting systems of differential equations for the unknown displacement functions are solved analytically. Element stiffness matrices can be calculated from the appropriate solution subsets for bounded and unbounded domains. From the inherent field expansion in the scaling direction, field exponents and coefficients can be calculated directly, which is of special interest to the analysis of notch and crack problems.

Incubation time based fracture mechanics

11756
Tue·14:00·1

Yuri Petrov
St Petersburg State University, Russia

Examples illustrating typical dynamic effects inherent in fast transitional processes are represented. A unified interpretation for both fracture in solids and a number of abrupt structural transformations in continua using the structural-time approach based on the new concept of the fracture incubation time is given. Examples of different physical processes considered in the paper show the fundamental importance of investigation of incubation processes preceding abrupt structural changes (fracture and phase transitions) in continua under intense pulsed actions. The fracture incubation time is evidently a universal basic characteristic of the dynamic strength and must become one of the main material parameters to be experimentally determined (measured).

The problem of co-linear twin cracks in elastic wave field

10398
Tue·14:05·1

Bing-zheng Gai† and Cao Ning
Harbin Institute of Technology, China†

This delegate supplied a paper but no abstract.

Multiscale energy momentum tensor and its application to fracture

10595
Tue·14:10·1

Shaofan Li
University of California at Berkeley, USA

Continuum theory of defects has been revised through the development of variational defect potentials. These defect potentials and their corresponding variational principles provide a basis for constructing a new class of conservation laws associated with compatibility conditions of continua. These conservations laws represent configurational compatibility, which is dual to the concept of configurational force, and it is independent of constitutive behaviors of continua. The contour integral of the corresponding conservation law is path-independent, if the integral domain is defect-free. We construct a multiscale energy momentum tensor by combining configurational force and configurational compatibility. In this paper, we shall discuss applications of the multiscale energy momentum tensor to ductile fracture, from which we have developed a multiscale Griffith criterion for elasto-plastic fracture under small scale yielding condition.

Thermal shock solution of a functionally graded material plate with arbitrary thermomechanical properties and a surface crack

10608
Tue·14:15·1

Li-cheng Guo† and Naotake Noda
Harbin Institute of Technology, China†

The thermal shock fracture behavior of a functionally graded material (FGM) plate with arbitrary thermomechanical properties and a surface crack is studied. In most of the published papers, in order to obtain analytical solutions, the thermomechanical properties of the FGM are usually assumed to be very particular functions and hence not practical. Greatly different from this, an analytical method combining a perturbation method and a piecewise model is proposed to obtain the transient temperature field and thermal stress intensity factor (TSIF). Integral transform, residue theory and the theory of singular integral equation are used. It is found that the method is very efficient to solve the thermal-shock problem and the TSIF can be affected by the distribution of the thermomechanical properties. Moreover, the peak value of the transient TSIF is much larger than the steady one. Therefore, it is much easier to result in a failure by the thermal shock than the steady thermal loading.

Stress fields near mode II interface crack tip of two dissimilar orthotropic composite materials

11022
Tue·14:20·1

Li Junlin† and Shaoqin Zhang
Taiyuan University of Science and Technology, China†

The interlaminar fracture problem of two dissimilar orthotropic composite materials interface crack subjected skew symmetric loadings was studied. In virtue of complex function method of composite material, a class of boundary value problems of partial differential equations set were discussed. When secular equations' discriminants were more than zero, constructing new stress functions, two systems of eight racks linear equations could be obtained. The theoretical solutions of stress fields and displacement fields near mode II interface crack tip were obtained. The results display that the stress fields have r singularity of $-1/2 + \varepsilon j$ ($j = 1, 2$) and it eliminates the oscillation (ε_1, ε_2 are bi-materials parameter). The displacement fields have not the embedding of the upper and lower sides of the crack. The stress fields and displacement fields of mode I and mode I+II orthotropic bi-materials near interface crack tip can be obtained similarly.

Energy analysis of the brittle fracture of solid with cracks

11276
Tue·14:25·1

Igor Dunaev† and Vladislav Dunaev
Kuban State Techology University, Russia†

The energy analysis of the thermodynamic condition for brittle fracture of solids at single loading and constant temperature based on the Rice–Drucker method is investigated for the two known models which describe an increment of defect (crack) surface area. In the first model, on sufficiently far surface from a defect, the stress values remaining the same before and after the incrementation of defect surface area. After calculations this model leads to the Griffith's criterion, in which the alteration of entropy constituent of internal energy is equal to zero. In the second model, on sufficiently far surface from a defect, the displacements remaining the same before and after the incrementation of defect surface area. After calculations this model leads to a new criterion, in which generally, the alteration of entropy constituent of internal energy does not equal zero. The test problem of fracture of a plate with crack at uniform tension or compression is solved.

Strain-energy criteria and fracture of plastic bodies in a neighborhood of strain concentrators

11318
Tue·14:30·1

Anastasia Bukhanko† and Alexander Khromov
Samara State Aerospace University, Russia†

The approach to definition of fracture criteria which include energy dissipation (together with strains) as the parameter characterizing a strain history is suggested. The model of ideal rigid-plastic body is put in the approach base. The plasticity condition connected with level lines of strain states surface of an incompressible plastic body is suggested. Strain fields and fracture processes in the neighborhood of strain concentrators are investigated on the basis of suggested criteria (including under low-cycle plastic deformations). Problems of uniaxial deformation of specimens with angular notches (with blunt point and without it) in the conditions of plane strain, of plane stress and of axisymmetric strain are considered. For more complex models of deformable mediums the approach to construction of numerical-analytical methods of analysis of strain fields and of fracture processes connected with them is suggested.

Support to rock excavations provided by adhesive liners

11776
Tue·14:35·1

Herven Abelman† and David Mason
University of the Witwatersrand, Johannesburg, South Africa†

We consider a long cylindrical excavation of circular cross-section in rock which is subject to a uniform shear at infinity. It is surrounded by an elastic medium consisting of three cylindrical regions which could represent two firmly bonded liners and the rock mass or one bonded liner with penetration of liner material into the rock mass. The purpose of this talk is to obtain a perturbation solution for the stress and displacement in each region using the theory of plane strain. The results will be used to investigate the support mechanisms provided by a system of two liners and penetration of liner material into the rock mass. The components in the system may be stiff layers of shotcrete, thin flexible shotcrete layers, very thin spray-on liners or wire mesh. The support characteristics will be very different for each liner system. A liner component may perform differently as an individual liner than as a component of a liner system.

Research on mixed mode and mode II crack growth in orthotropic composites by caustics method

10892
Tue·14:40·1

Zheng Li,† Kezhuang Gong and Kan Feng
Peking University, China†

Dynamic caustics method is firstly developed to analyze the crack propagating process of mixed mode and mode II fracture in orthotropic composites. Influence of the crack growth velocity and fracture mode on caustics curves is discussed theoretically for both mixed mode and mode II crack. Meanwhile corresponding experiments are carried out to study on the dynamic fracture behaviors of unidirectional fiber reinforced composites with mixed mode or mode II crack separately. By analyzing the shadow spot patterns during the crack propagation process recorded by a high speed camera carefully, dynamic fracture toughness and crack growth velocity of orthotropic composite are determined. Moreover, the meso-analysis of fracture sections is performed by a scanning electron microscope, to reveal the dynamic fracture mechanism of fiber reinforced materials.

3D interface crack in fully coupled electromagnetothermoelastic multiphase anisotropic composites

10614
Tue·14:45·1

BoJing Zhu,† Shaohua Yu, Taiyan Qin and Yaolin Shi
Graduate University of Chinese Academy of Sciences, China†

This contribution presents a new theory with hypersingular intergro-differential equation (HIDE) method to analyze the 3D interface crack in multiphase anisotropic electro-magneto-thermo-elastic composites under extended electro-magneto-elastic coupled loads through intricate theoretical analysis and numerical simulations. The 3D interface crack is reduced to solving a set of HIDEs coupled with extended boundary integral equations by using the Green's functions, in which the unknown functions are the extended displacement discontinuities. Analytical solutions for the extended singular stresses, the extended stress intensity factors and the extended energy release rate near the dislocations front are provided. The numerical solutions of extended stress intensity factors and the extended energy release rate varying with the shape of crack are discussed.

Fracture simulation of concrete using fractal approach and lattice model: validation by AE study

10027
Tue·16:00·1

Remalli Sagar† and Raghu Prasad
Indian Institute of Science, India†

A study on fracture simulation in concrete using fractal approach and 2D lattice model is presented. A three-point bend specimen is modeled using triangular lattice network. Singular fractal functions which are monotonically increasing functions and differentiable almost everywhere with zero derivative throughout their domain have been used to simulate the constitutive law for concrete. A simple approach followed by Mosolov [6] to distribute mass on a line continuously divided to form a Cantor dust is employed to generate constitutive law of concrete, which is used in the 2D lattice model. Load versus CMOD plot thus obtained from lattice model analysis shows softening behavior of concrete which agrees with the experimental results. There is a good correlation between the number of failed members in lattice and the number of acoustic mission events. Both are less just before the peak load and increase significantly after the peak load till the failure.

Multiple cracking of an embedded concretion

10833
Tue·16:20·1

Dominique Leguillon,† Daniel Quesada, Claude Putot and Eric Martin
Centre National de la Recherche Scientifique, France†

As well as cavities, embedded concretions and fossil inclusions are known to be possible sites of fracture initiation in rocks under compressive loads (Bessinger *et al.*, 2003). A picture of these authors shows 5 parallel cracks in a calcareous inclusion embedded in sandstone. The cracks spacing is small and strictly incompatible with a mechanism of successive failures and reloading, the only explanation is that these failures occur simultaneously and thus without any shielding effect. The mixed criterion proposed by Leguillon (2002) is able to predict such a fracturing mechanism. It is strongly related to a size effect, larger the inclusion diameter and higher the number of possible fractures. A similar reasoning can be applied to other situations like transverse cracking in composite laminates for instance.

Spontaneous crack propagation in functionally graded materials **10145** Tue·16:40·1

Dhirendra Kubair† and Sandip Haldar
Indian Institute of Science, Bangalore, India†

The effect of material inhomogeneity on the dynamic fracture response of a crack in functionally graded materials is numerically investigated. Spontaneous planar crack propagation in FGMs is simulated using a novel spectral scheme. The material properties are assumed to vary in the direction perpendicular to the crack faces. An intrinsic material property length scale controls the rate of material property variation. Our results showed that the fracture resistance increases when the material becomes stiffer (increase in modulus and density), while the fracture resistance reduces for materials that progressively become compliant away from the weak-plane. The increase (or decrease) in the fracture resistance is indicated by the decrease (or increase) in the crack opening displacement and velocity of propagation. Fracture resistance of the graded system can be tailored by suitably choosing the half-spaces on either side of the weak-plane.

Crack bridging model for nanocomposites **10165** Tue·17:00·1

Mikhail Perelmuter
Institute for Problems in Mechanics, Russia

The crack bridging model is proposed for study of fracture toughness of nanocomposites. It is supposed: there are bonds (nanoparticles or nanotubes) which constrain the opening between the crack surfaces; the size of a zone, filled with the bonds (the bridged zone) is comparable to the whole size of the crack; the bridged zone is a part of the crack with nonlinear time-dependent bonds between the crack surfaces. The analysis of the crack growth consists of: molecular analysis of the stresses and the adhesion between the matrix and nanofiller to model the bonds deformation law; analytical and numerical evaluation of the stresses around the crack; development and application the non-local crack growth criterion to analyze the fracture parameters of nanocomposites. These steps are examined with the samples for different kinds of materials. In frames of the model the macroscopic parameters of nanocomposites are modeled on the base of the nanoscale parameters of the material structure.

Non-linear crack growth in short steel fibre reinforced concrete: modeling and experimental verification **10129** Tue·17:20·1

Andrejs Krasnikovs,† Andrejs Pupurs and Olga Kononova
Riga Technical University, Latvia†

During the fracture process steel fibres are bridging the crack in the concrete, providing resistance to crack propagation and crack opening. Developed structural SFRC fracture model was based on single fibre pull-out law. Concrete with different geometry and size steel fibres was observed. Fibre pull-out law (pull-out load as a function of crack opening) for each type of steel fibre (depending on the orientation and length) was determined experimentally (and was obtained using FEM). During crack growth, different crack parts (along the crack) are bearing different load, forming non-linear part of load-deflection curve. As the load carried by each fibre at a constant crack opening is known, the corresponding total bending load P for a beam was obtained through equilibrium conditions (Monte-Carlo simulations and experimental results were used for fiber distributions along the crack surface). Numerical predictions were compared with macro-experiments.

A computational method for three dimensional finite deformation fracture

11544
Wed·10:40·1

Dana Mueller-Hoeppe,† Stefan Loehnert and Peter Wriggers
Leibniz Universitaet Hannover, Germany†

We present a computational method for three dimensional finite deformation numerical fracture mechanics simulations. The numerical model is based on the extended finite element method and applied to brittle fracture processes. Since the deformation of the elastic material in the vicinity of the crack front is strongly nonlinear, a finite deformation model and a Neo-Hookean material model is used. Several examples show the performance of the method and illustrate the interaction of microcracks and macrocracks.

A computational approach for fatigue crack propagation in ship structures under random sequence of clustered loading

11551
Wed·11:00·1

Yoichi Sumi† and Teppei Okawa
Yokohama National University, Japan†

A simulation method is proposed for simultaneously propagating multiple fatigue cracks in marine structures, based on step-by-step finite element analyses. In this problem, it is necessary to take into account the load histories induced by sea waves, which may be composed of a random sequence of certain clustered loads. In the proposed crack growth model, the crack opening and closure behavior is simulated by using the modified strip-yielding model, and the effective tensile stress intensity range is calculated by considering the contact of plastic wake along the crack surfaces. The validity of the present model is examined by fatigue tests under non-constant amplitude loading. The usefulness of the developed method is demonstrated for a ship structural detail under simulated random load sequences. The estimated fatigue crack growth shows considerable retardation, so that the conventional fatigue life assessment may be rather conservative for design purpose.

Dominant mechanism for crack propagation in nonplanar interface

12063
Wed·11:20·1

Abhijit Dasgupta,† Joseph Varghese and Koustav Sinha
University of Maryland, USA†

Interfacial bonding between dissimilar metallic materials often results in wavy non-planar intermetallic layers. Examples include intermetallic layers between solder and bond pads in electronic assemblies. Published data reveals that interfacial waviness decreases with continued thermal aging, resulting in reduction of the apparent fracture resistance of the interface (Xu and Pang, 2006; Yao and Shang, 1996). There has not been any fundamental systematic study to understand what fraction of this loss in fracture resistance is due to reduction in the waviness and what fraction is due to intrinsic changes in the interfacial fracture energy caused by aging-induced chemical changes. This paper provides fundamental insights into the relative contributions of these two mechanisms for thermal aging of solder-bond pad interfaces in electronic assemblies, based on detailed stress analysis and on crack-shielding mechanisms at interfaces of dissimilar materials (Evans and Hutchinson, 1989).

Simulation of crack propagation in functionally graded materials **10633** Wed·11:40·1

Li Ma,† Zhi-Yong Wang and Lin-Zhi Wu
Harbin Institute of Technology, China†

This paper addresses the numerical simulation of mixed-mode crack propagation in Functionally Graded Materials (FGMs) by means of eXtended Finite Element Method (XFEM). Each step of crack growth simulation consists of the calculation of the mixed-mode stress intensity factor by means of a non-equilibrium formulation of the interaction integral method, determination of the crack growth direction based on a specific fracture criterion. A specific fracture criterion is tailored for FGMs based on the assumption of local homogenization of asymptotic crack-tip fields in FGMs. The present approach uses a user-defined crack increment at the beginning of the simulation. Crack trajectories obtained by the present numerical simulation agree well with available experimental results for FGMs. The computational scheme developed here serve as a guideline for fracture experiments on FGM specimens (e.g. initiation toughness and R-curve behavior).

Determination of the effective material properties of a linear elastic material with a randomly distributed microcracks by the three level finite element method **11208** Wed·12:00·1

George Mejak
University of Ljubljana, Slovenia

A new computational method based on the finite element method is presented. The method is suited to problems with complex microgeometry where a direct numerical resolution of the micro scale by the standard finite element method is too expensive. It has two levels of static condensation, at the micro and the meso levels. Comparing with the standard finite element method it is very efficient. It's efficiency ratio is of order $O(p^{2/3})$ where p is a number of micro cells and of order $O(h^{-6/7})$ where h is a standard finite element mesh size. Viability of the method is illustrated by computation of the effective material properties of a linear elastic material with a randomly distributed microcracks. Variation of the effective Young modulus with respect to the crack density parameter is given.

Damage tolerance of a sandwich panel with square honeycomb core **11319** Wed·12:20·1

Ignacio Alonso† and Norman Fleck
Cambridge University, UK†

The compressive fracture strength of a sandwich panel, with a centre-cracked core made from an elastic brittle diamond-celled honeycomb, is explored by finite element simulations. The honeycomb fails when the local stress attains the compressive or tensile strength of the solid, or by local buckling of the cell walls. The results indicate that conventional linear elastic fracture mechanics applies when a K-field exists on a scale larger than the cell size. But there is a regime of geometries for which no K-field exists; in this regime the stress concentration at the crack tip is negligible and the net strength of the cracked specimen is comparable to the unnotched strength. Predictions are given for the unnotched strength, and for the fracture toughness of the lattice.

Assessment on the structural integrity based on 3D crack growth simulations

10507
Wed·12:40·1

Wilhelm Weber,† Paul Steinmann and Günther Kuhn
Institute of Applied Mechanics, Germany†

The accurate simulation for 3D fatigue crack growth as the basis of the assessment of the structural integrity is presented. The crack propagation is modelled in terms of linear elastic fracture mechanics. Beside the stress intensity factors, the non-singular T-stresses are considered within the 3D crack growth criterion. Furthermore, it includes the knowledge of 3D corner singularities. A sophisticated predictor-corrector scheme guarantees very accurate simulation results to predict component lifetimes.

Exact solution of a penny-shaped crack in piezoelectric materials with electric saturation at the crack tip

10323
Thu·11:00·3

Weiqiu Chen
Zhejiang University, China

Most commercial piezoelectric materials of practical importance are piezoceramics that are very susceptible to cracking. This has greatly stimulated the study on crack problems of piezoelectric materials in recent decades. The extended potential theory method for piezoelasticity is employed to account for the electrically yielded phenomenon (electric saturation) around a penny-shaped crack tip for the axisymmetric loading. The Dugdale model proposed to simplify the plastic deformation analysis near the crack tip in nonlinear fracture is adopted. The exact solutions of the resulting integro-differential equations are derived in the case of uniform loading, with the outer radius of the electric saturation annular strip determined from the condition of no singularity of electric field at the crack tip. Explicit expressions for the electroelastic field at any point in the half-space thus can be obtained.

Pre-existing fluid driven fracture in permeable rock

11346
Thu·11:20·3

David Mason† and Gideon Fareo
University of the Witwatersrand, South Africa†

A fluid-driven pre-existing fluid-filled fracture in permeable rock is considered. The fluid in the fracture is described by lubrication theory. The PKN model in which the fluid pressure is proportional to the fracture half-width is adopted. The evolution of the fracture is reduced to a non-linear diffusion equation for the half-width. A similarity solution which describes a pre-existing fracture is derived using the Lie point symmetries of the non-linear diffusion equation. The boundary value problem for the ordinary differential equation is reformulated as a pair of initial value problems. Analytical solutions for two special special cases and numerical solutions are obtained for fluid injection and extraction at the fracture entry and for leak-off and inflow at the fluid/rock interface.

Unidirectional 'DCB' and 'ENF' specimens: a comparative study between finite elements and higher order beam theories

11469
Thu·11:40·3

Raghu Prasad† and Pavan Kumar
Indian Institute of Science, India†

Delamination is one of the major sources of failure in laminated composite structures. Double cantilever beam (DCB) and end notch flexure (ENF) specimens are the most commonly used test specimens, respectively, for the determination of mode I and mode II interlaminar fracture toughness

of composites. In this paper, 2D finite element analysis (FEA) of unidirectional composite DCB and ENF specimens has been carried out for various span-to-depth ratios and crack lengths. Strain energy release rate (SERR) has been calculated using virtual crack closure technique (VCCT). The SERR values obtained from VCCT in conjunction with FEA have been compared with those obtained from recent higher order beam theory based formulations. Thus, a check on the performance of stress analysis models based on higher order beam theories, vis-a-vis, well established finite element software in conjunction with VCCT has been provided in determining the SERRs of unidirectional composite DCB and ENF specimens.

Microstructural simulation on the brittle versus ductile transition of nanocrystalline metals

11916
Thu·12:00·3

Wei Yang† and Fan Yang
Zhejiang University, China†

Microstructural simulation for a sample of nanocrystallion metal with a crack is conducted in this work. The structural evolution scheme is employed to model the mass flow, the grain boundary cavitation, and the crack growth of the specimen under remote loading. The scheme leads to a system of ordinary differential equations that can be solved by Euler integration. The simulation validates the proposal that the ductile versus brittle transition of nano-grained metals is dictated by the competition of creep deformation promoted by grain-boundary kinetics, and the decohesion of grain boundaries. The simulation results in the parameter space agree with the theory proposed by the authors.

Mixed-mode fracture in viscoelastic orthotropic material

10645
Thu·12:20·3

Rostand Pitti,† Octavion Pop and Frédéric Dubois
Universite de Limoges, France†

This paper deals with a new method separating mixed mode crack growth in viscoelastic material. The analytical approach results from an original integral parameter called M, based on conservative laws, path independent integral and a combination of real and virtual displacement fields inducing a bilinear form of free energy density. The original idea is to propose also, a new numerical specimen giving at the same time, viscoelastic properties, and fracture parameters. That way, thanks to finite element software CASTEM, mechanics fields computed by an incremental viscoelastic formulation, and energy release rate computed with M_v-procedure, are obtained. In order to have, in the time domain, the critical time and the crack initiation, a dichotomy on the time and the crack length is performed. As results, a new specimen is justified, and the numerical evolutions of energy release rate versus crack length are posted in opening mode, shear mode and mixed mode.

SM08 :: Geophysics and geomechanics

Chairs: Nadia Lapusta (USA) and Ioannis Vardoulakis (Greece)

Mon	16:25–17:45	Room 1	Lectures
Tue	15:00–15:10	Hall B	Seminars
Tue	16:00–17:40	Room 8	Lectures
Wed	10:40–12:40	Room 8	Lectures

Modelling high pressure shear using breakage mechanics

10201
Mon·16:25·1

Itai Einav,† Giang Nguyen and Ioannis Vardoulakis
The University of Sydney, Australia†

The grain size distribution (gsd) is one of the most important characteristics of granular materials, and should therefore be vitally important in numerical modelling. In crushable granular materials, the gsd is constantly shifting towards smaller particles, particularly under high confining pressures. Experiments show that the continuously evolving grading governs the inelastic behaviour of the material. The micro-scale phenomenon of grain crushing can affect the stability of the supporting material layers of macro-engineering structures, e.g. landslides in sands and cataclasis in rocks. The response of crushable granular materials under high confining pressures is numerically studied using the framework of continuum mechanics, by adopting a constitutive model that rigorously accounts for the evolving gsd. The behaviour of the material in ring-shear tests is numerically simulated and the ability of the model to predict the evolving gsd is illustrated during the stages of loading.

Mechanical characteristics of seismic waves estimated from earthquake-induced structural failures

10628
Mon·16:45·1

Koji Uenishi
Kobe University, Japan

The physical properties of seismic waves are usually estimated inversely from seismological recordings (seismograms). Here, from the dynamic structural damage patterns generated in tunnels and slopes by earthquakes, we try to evaluate the mechanical characteristics of relevant seismic waves. The elastodynamic analysis shows only waves in relatively high frequency range may induce the observed unique structural failures, although the influence of high-frequency seismic waves on the damage of human and natural structures is still believed to be very small and such high frequencies may be difficult to detect or even intentionally filtered out in ordinary seismological observations. The present study suggests that, contrary to the structures on the surface, underground structures and slopes subjected to dynamic waves vibrate with their surroundings and they may function as sensors that respond only to waves of specific type, frequency and propagation direction.

Mechanisms of dynamic friction at slip rates appropriate for earthquake faulting

11931
Mon·17:05·1

Yuri Fialko† and Kevin Brown
University of California, San Diego, USA†

Experimental studies of rock friction in the velocity range of cm/s to m/s and normal stresses of order of megapascals indicate that the effective coefficient of friction undergoes a complex evolution including a primary weakening phase, transient strengthening, and a secondary weakening phase. A rapid initial decrease in the coefficient of friction can be explained in terms of thermally activated plastic deformation of particles in a finite gouge layer. Transient strengthening observed in low pressure experiments results from incipient melting and flattening of the sliding asperities, and an overall increase in the real contact area. Peak friction is achieved when the nominal slip interface is covered by a continuous film of melt, and secondary weakening is associated with shear thinning of a melt layer due to temperature dependent melt viscosity.

3D modeling of dynamic and quasi-static fault slip: interaction of dynamic rupture with a stronger patch over several earthquake cycles

10548
Mon·17:25·1

Nadia Lapusta† and Yi Liu
California Institute of Technology, USA†

Slip processes on faults involve dynamic ruptures and quasi-static slip, which influence each other by changing stress and other fault conditions. Hence it is important to simulate the entire fault slip history. Based on previous 2D studies, we have developed a 3D methodology for simulating long-term fault slip with occasional dynamic rupture episodes. It incorporates rate and state friction, slow tectonic-like loading, and all inertial effects during dynamic rupture. As an implementation example, we study interaction of dynamic rupture with a compact stronger patch and find that the effect of the patch on rupture propagation is greatly diminished after several simulated earthquakes due to redistribution of stress. At the same time, the patch has long-term effects on slip accumulation patterns. We compare our results to a simplified, quasi-dynamic, simulation approach widely used in earthquake studies and suggest modifications to the simplified approach that improve the comparison.

Earthquake source mapping using strong motion array data

10706
Tue·15:00·B

Narayana Iyengar† and Raghukanth Gudemella
Indian Institute of Science, India†

This paper describes a novel engineering approach to map the geometry of the rupture zone from surface level strong motion records. The ground motion is taken as the response of the near source region, modeled as layered elastic half-space, to the rupture at the fault level. The forces developed at the source are represented by a sequence of double couples, applied at unknown locations inside the half-space. The magnitude, rise time and the point of application of the double couples are found by minimizing the error between the analytically derived surface level station response and the recorded SMA data. A plot of the locations of the double couples directly provides a picture of the rupture zone, compatible with the recorded strong motion array data. Numerical results, along with available comparisons are presented for the San Fernando, USA (9.2.1971), Imperial Valley, USA (15.10.1979), Uttarakashi, India (20.10.1991) and Chi-Chi, Taiwan (20.9.1999) earthquakes.

Using fundamental solutions of mechanics of deformable rigid body in geomechanical problems

10864
Tue·15:05·B

Andrew Krupoderov† and Michael Zhuravkov
Belarus State University, Belarus†

Paper is devoted to using of fundamental solutions of mechanics of a deformable rigid body in geomechanical problems. The technology and some examples of using static fundamental solutions at studying processes of motion of Earth surface in rock's massive are described. Also some examples of using dynamic fundamental solutions at studying wave processes in rock's massive are considered.

Fluid-driven fracture growth along an existing natural fracture

11132
Tue·16:00·8

Xi Zhang† and Rob Jeffrey
Commonwealth Scientific and Research Organisation, Australia†

An increase in fluid pressure, arsing from, for example, injection into a wellbore, will open existing fractures in the rock mass when it exceeds in-situ normal stresses acting across the fracture plane. On the other hand, transient flow can occur into the hydraulically conductive natural fracture even if the fluid pressure is less than that required to open the fracture. Numerical results are presented for the transition from transient flow to opening-mode hydraulic fracturing along a stepped natural fracture in the case of constant injection rate. Using the cubic law, the coupling between fluid flow and elastic rock deformation is solved in terms of an implicit scheme using the Finite Difference Method and the Displacement Discontinuity Method. The local fracture conductivity depends on the interplay of fluid pressure and rock stresses. Restriction of the fracture path can result in flow limitation, leading to abnormal treating pressure and fracture path alteration.

Predicting behavior in granular materials via multiscale computations

11206
Tue·16:20·8

Jose Andrade
Northwestern University, USA

In this paper, a novel framework for behavior prediction of granular materials via multiscale concepts is presented. The theoretical developments depend crucially on elastoplasticity and exploit the concept of direct numerical simulation within a unit cell to bypass phenomenological hardening laws. The framework allows for extraction of key plasticity parameters hierarchically and directly from the micromechanics. The predictive capability of the method is demonstrated by way of example. The simplicity and accuracy of the method are remarkable and open the door for more realistic computations of boundary value problems in granular media were phenomenology is prone to breaking down.

Laboratory experiments and theoretical studies of rupture modes and supershear transition

11522
Tue·16:40·8

Xiao Lu,† Ares Rosakis and Nadia Lapusta
California Institute of Technology, USA†

Dynamic ruptures on frictional interfaces can propagate either in the crack-like mode, with local sliding duration comparable to the overall rupture duration, or the short-duration pulse-like mode. Seismic inversions indicate that earthquakes favor the pulse-like mode, and mechanisms for such behavior continue to be vigorously debated. This study presents first experimental observations of spontaneous pulse-like and crack-like ruptures. Systematic variation from pulse-like to crack-like modes is found as the prestress level is increased. The experiments also reveal that both rupture modes can transition to intersonic speeds. Measurements of normal displacements indicate there is no interface opening during sliding and the normal stress variations at the measurement location are insignificant. The results are consistent with theoretical studies of strongly velocity-weakening interfaces and provide indirect evidence for importance of velocity-weakening friction in earthquake dynamics.

Mathematical theory of plasticity for frictional materials

10358
Tue·17:00·8

Kristian Krabbenhoft
University of Newcastle, Australia

We consider the extension of the classical mathematical theory of plasticity to frictional materials. It is shown that the apparently nonassociated plastic flow often observed in such materials can be accounted for by models that are variational in structure. In addition, the theory predicts a number of new terms and functional relationships that appear to have particular relevance to granular materials. The theory is illustrated by the construction and calibration of a simple five-parameter model for sands.

Earthquake nucleation on geometrically complex faults

11917
Tue·17:20·8

Guanshui Xu,[†] James Dieterich and Zijun Fang
University of California at Riverside, USA[†]

Earthquake nucleation processes on geometrically complex faults are studied. The focus is on the geometrical effects on nucleation location and occurring time. The model is built on the variational boundary integral formulation of fault slip operated under a rate- and state-dependent friction law, which includes evolution of frictional state under the combined effects of time, slip and normal stress. The results consistently show that the variation of normal stress on nonplanar faults alters sliding resistance, significantly affecting nucleation location and occurring time.

Spectral element simulations of dynamic rupture along non planar faults

11918
Wed·10:40·8

Jean-Pierre Vilotte[†] and Gaetano Festa
Institut de Physique du Globe de Paris, France[†]

Earthquake source dynamics provides key elements for the prediction of strong motion. However generation of high frequency wave by seismic faulting is a long standing issue for seismologists. Geological and geophysical observations indicate that large strike slip events propagate along faults of complex geometries. Steep variation in the rupture direction may have profound effect on the rupture propagation speed and the seismic radiation. We investigate numerically, using a non smooth spectral element method, the dynamics and the seismic radiation associated with rupture propagation along a kink fault geometry in the inplane case. Slip weakening friction is assumed along the fault. Shear wave radiation is associated with the rupture change direction as well as a static stress concentration. In contrast to the antiplane case, no significant change of the rupture speed is observed at the kink. Implications for high frequency generation ans frictional models will be discussed.

A multiscale modelling of damage and time dependent plastic behavior of cohesive rocks: formulation and numerical applications

11937
Wed·11:00·8

Jian-Fu Shao,[†] Ariane Guery, Fabrice Cormery and Djimédo Kondo
Laboratoire de Mécanique de Lille, France[†]

We propose a 3D micromechanical model of damage and time-dependent plastic behavior of a cohesive geomaterial, the Callovo–Oxfordian argillite. This heterogeneous material is made up of 3 constituents: an elastoviscoplastic clay matrix; elastic quartz minerals and elastic damage calcite grains. The macroscopic constitutive law is obtained by adapting the incremental homogenization method of Hill to the context of non associative plasticity. Its unified formulation allows modeling not only the time dependent behavior of the argillite, but also its plastic damage response. The model is first validated by comparison with Finite Element solutions on a unit cell and then applied to predict the responses of the argillite in connection with its mineralogical compositions. The validity of the model is shown for various loading paths by comparing its predictions to experimental data. Finally, the model is implemented and used for structures involved in a geomechanical waste storage project.

Multi-phase coupled elasto-viscoplastic analysis of unsaturated soil slope during seepage flow

11436
Wed·11:20·8

Fusao Oka,[†] Ryosuke Kato, Shinya Yamazaki and Sayuri Kimoto
Kyoto University, Japan[†]

In the present study, a deformation-seepage coupled analysis that can simultaneously take account of the unsaturated seepage flow and the soil deformation is proposed. An air-water- soil coupled elasto-viscoplastic large strain finite element analysis has been developed to analyze slope stability during the seepage flow by incorporating the unsaturated seepage characteristics. In the analysis, we have used a three-phase coupled analysis method based on the theory of porous media. The result of the present analysis shows that the strain localization due to seepage flow can be clearly simulated. In addition, when we consider the overflowing over the embankment, the deformation of river embankment becomes larger than the case with only consideration of the seepage flow. From the analysis we found that the proposed hydro-mechanically coupled analysis method is an effective tool to estimate the slope stability.

Thermomechanics of faults

11604
Wed·11:40·8

Emmanuil Veveakis,[†] Jean Sulem and Ioannis Vardoulakis
National Technical University of Athens, Greece[†]

Shear heating of a temperature dependent material is considered to be the main mechanism that leads to thermal pressurization and thus to the strength weakening of faults during earthquakes and catastrophic landslides (Rice 2006; Veveakis *et al.*, 2007). Indeed, when thermal softening and velocity hardening is introduced to the constitutive behaviour of the fault material, thermal runaway occurs inevitably after some period of quasi-stable creep (Veveakis *et al.*, 2007). However, this constitutive behaviour has been proven to be highly unstable, prone to no recovery mechanism. In this study we extend that study, by focusing on the transition from aseismic creep to seismic slip in faults. We show that this transition can be periodic, since the spring-slider model with a two state variables friction law presents a periodic transition from stable to unstable solution through a Hopf bifurcation.

10851
Wed·12:00·8

Propagation of shear waves in an elastic layer with void pores

Prakash Pal
Indian School of Mines University, India

The present paper investigates the study of propagation of shear waves in a poro-elastic layer resting over a poro-elastic half-space. Pores contain nothing of mechanical or energetic significance. The study reveals that such a medium generates two types of shear waves. The first shear wave front depends upon the modulus of rigidity of the elastic matrix of the medium and is the same as the Love wave in an elastic layer over an elastic half-space. The second wave front depends upon the change in volume fraction of the pores. As the first wave front is well-known, the second front is evaluated numerically for different values of void parameters. It is observed that the second wave front is many times faster than the shear wave in the void medium due to change in volume fraction of the pores and is thus significant.

10847
Wed·12:20·8

Non-Euclidean model of the zonal disintegration of rocks around an underground working

Mikhail Guzev
Russian Academy of Sciences, Far Eastern Branch, Russia

The non-Euclidean continuum model for the description of the stress-field distribution around underground workings with a round cross section is considered. From the physical viewpoint, the non-Euclideanness parameter determines the incompatibility of deformations in a rock. It is shown that disintegration zones can be identified with the parts of the rock in which this parameter takes on the maximum values and the force discontinuity criterion for the medium holds. An analysis allows one to relate the macroscopic characteristics of zonal rock fracture around a working to the non-Euclideanness parameter.

SM09 :: Impact and wave propagation

Chairs: Narinder Gupta (India) and Rod Clifton (USA)

Mon	14:00–16:00	Room 8	Lectures
Tue	14:00–14:55	Room 3	Seminars
Tue	16:00–17:40	Room 10	Lectures
Thu	11:00–12:40	Room 4	Lectures
Thu	14:00–14:35	Room 1	Seminars

Dynamic strain localization and fragmentation

11502
Mon·14:00·8

Krishnaswamy Ravi-Chandar† and Haitao Zhang
The University of Texas at Austin, USA†

The tensile constitutive and failure behavior of ductile metals at high strain-rates—between 1000 and 15000 per second—is considered. An electromagnetically driven expanding ring experiment is used as the primary tool for examining the material behavior in this range of strain rates. The details of the experimental design, diagnostic methods and interpretation of the localization and fragmentation will be discussed. Mechanistic and statistical aspects of necking and fragmentation, modeled through conventional elasto-plastic theory and the idea of the Mott release waves, will be described. Similarities and differences between quasi-static and dynamic localization will be explored through variation of specimen geometry, size and inherent material properties. Application of the idea to blast protection of structures and to manufacturing processes will be discussed as the primary motivating problems.

A substructure technique for impact-induced transient wave of discontinuous flexible system with wave geometric dispersion

11527
Mon·14:20·8

Yunian Shen† and Xiaochun Yin
Nanjing University of Science and Technology, China†

A dynamic substructure technique is presented to study the contact-impact problems of complicated flexible system. The impact system consists of a cantilever bar with discontinuous cross section and discontinuous material longitudinally struck by a rigid mass, and the transverse inertia of the bar is considered. Based on the Lagrange equation and fixed interface mode synthesis method, the transient dynamic equations are derived and expressed by reduced generalized coordinates. The transverse kinetic energy is taken into account. The numerical results show that the substructure technique can be applied to the impact problem of more complicated flexible systems. The impact force responses and the propagations of impact-induced transient waves can be simulated reasonably, even though the wave geometric dispersion phenomenon takes place.

Dynamic test of the main aircraft landing gear with failure

11865
Mon·14:40·8

Wieslaw Krason,† Jerzy Malachowski and Rafal Kajka
Military University of Technology, Poland†

Dynamic analyses of the landing gear are conducted to provide capabilities to forecast their behavior under hazardous conditions. This kind of investigation with numerical methods implementation is much easier and less expensive than stand tests. Majority of the fatigue numerical analysis and prediction of the landing gear's lifetime is limited to the linear analysis and the local phenomena appearing around a failure. Such approach was developed at the first stage of the work. The influence of a failure on the complete landing gear system are subject of our consideration as well. Various 3D models of the landing gear part with failure were defined for the static FE analysis. Complete system of the main landing gear was mapped as the deformable 3D numerical model for dynamic analysis with LS-Dyna code. Experimental and numerical research of transport airplane's landing gear are discussed in this paper.

Modeling mechanical response and failure of ice submitted to high velocity impacts **12097** Mon·15:00·8

Yann Chuzel-Marmot,† Alain Combescure and Roland Ortiz
INSA Lyon, France†

This paper is devoted to the modeling of mechanical properties as well as failure of ice which may pass through airplane engines. A series of tests has been performed at ONERA to characterize the response of ice under this type of loadings. The dynamic failure has been observed using an extremely high speed camera (200 000 images/s). One can see how the failure progresses within the specimen during the dynamic fracture. The effects of velocity on compression and traction limit stress is also presented for strain rates up to 1000/s. Other experiments of impacts on a plate compare the effects of two impactors with same mass and same velocity: one is an ice small cylinder and the other is a water mass. The comparison shows the interest of modeling ice as a solid. The mechanical model chosen to model the ice is presented. It has been implemented in an explicit code. Comparisons of computed results with experiments are given.

Bloch–Floquet flexural waves and localised defect modes in thin elastic plate structures **11404** Mon·15:20·8

Natasha Movchan,† Ross McPhedran and Alexander Movchan
University of Liverpool, UK†

A mathematical model is presented for propagation of flexural waves within a thin elastic plate containing a periodic array of circular holes. A spectral problem is formulated for a biharmonic operator in an elementary cell of the periodic structure; the analytical solution is constructed in the form of a multipole series, and it satisfies the Bloch–Floquet conditions within the periodic structure. The dispersion diagrams are analysed for the two cases where the boundaries of holes are either clamped or free. A special attention is given to the low frequency stop bands and to the standing waves corresponding to the edges of the stop bands. We extend the analytical study to eigensolutions for periodically clamped elastic plates in the zero radius limit. We also consider a finite array of pinned points within a thin elastic plate. An exponentially localised defect mode created by removing one or several pins from the array is studied in detail.

Modelling stress wave propagation under biaxial loading using SPH **10107** Mon·15:40·8

Rajarshi Das† and Paul Cleary
CSIRO, Australia†

The paper examines the application of a mesh-free method Smoothed Particle Hydrodynamics (SPH) for modelling stress wave propagation in elastic solids under biaxial compression. To verify the SPH solutions, the same problem is analysed using the Finite Element Method (FEM). The solutions predicted by SPH were found to agree well with those obtained using FEM. A convergence study for different particle resolutions was performed against a fine-mesh finite element solution. In contrary to the theoretical second order accuracy, the order of convergence is found to decrease with decreasing particle resolution due to the effect of free edges. For a sufficiently fine resolution model, the method

approached the second order accuracy, whereas it performed midway between a first and a second order scheme for a relatively coarse model. This paper thus demonstrates the potential of SPH for accurate modelling of elastic wave propagation in solid materials subjected to biaxial compression.

Emergence of soliton trains in microstructured materials

11311
Tue·14:00·3

Andrus Salupere,† Merle Randrüüt and Kert Tamm
Tallinn University of Technology, Estonia†

Microstructured materials (alloys, crystallites, ceramics, functionally graded materials, etc) are characterised by various scales of microstructure. This circumstance should be taken into account when wave propagation in such materials is modelled. In the present paper wave propagation in microstructured media is studied based on hierarchical 'two wave' model equation and corresponding evolution equation ('one wave' equation), the first is of the Boussinesq type and the second of the Korteweg-de Vries type. Model equations are numerically solved by employing of the Fourier transform based pseudospectral method. Localised initial conditions are used for the Boussinesq type equation and harmonic initial conditions for the Korteweg-de Vries type equation. In both cases trains of solitary waves emerge from the initial excitation. Solitonic behaviour of these solitary waves is detected and analysed.

Propagation of surface SH waves on a half space coated with a nonlinear thin layer

11373
Tue·14:05·3

Ali Demirci,† Mevlut Teymur and Semra Ahmetolan
Istanbul Technical University, Turkey†

In this work the propagation of nonlinear surface SH waves on a half space coated with a layer of uniform thickness is considered. First, equations and boundary conditions given by Teymur representing the wave propagation are approximated under the thin nonlinear layer assumption. A new boundary value problem involving only the displacement function of the half space as an unknown is derived. The boundary condition of the approximation includes nonlinear material parameters of both the layer and the half space. Then the Nonlinear Schrödinger (NLS) equation is derived for the self modulation of SH waves by employing an asymptotic perturbation method. For examining the result of the thin nonlinear layer approximation the variation of the linear and nonlinear coefficients of the NLS equation with kh are calculated for various nonlinear models. These results are compared with the results of finite nonlinear layer given by Teymur and thin linear layer approximation given by Maugin *et al.*

Guided elastodynamic waves in functionally graded cylindrical structures

11412
Tue·14:10·3

Jacqueline Vollmann,† Laurent Aebi, Juerg Bryner, Nicolas Bochud and Jürg Dual
ETH Zurich, Switzerland†

The propagation of axisymmetric elastodynamic waves in cylindrical structures with various radial gradients of the elastic properties is calculated numerically with a finite-difference-time-domain-method. Due to axisymmetry the displacement field remains two-dimensional, consisting of a radial- and a longitudinal component. The multimode nature of the guided waves propagating along the axis is analyzed with a two dimensional spectrum analysis method providing dispersion relations. Up to 15 traveling wave modes are calculated. Results are provided for a radial transition function of the material properties which corresponds to a half period of a cosine function. These results are compared with the dispersion relation calculated for a homogeneous cylinder.

High velocity penetration into ground media **11479** Tue·14:15·3

Igor Simonov† and Yury Bivin
Institute for Problems in Mechanics, Russia†

The review summarizes long-term investigations on high-velocity penetration. The empirical laws of trajectory change and ricochet during oblique impact of both mono-projectile and a group of bodies have been studied. The peculiarities of penetration into a target disturbed statically or dynamically have been found. The penetration of axisymmetrical and spatial (star-like in the cross section) shapes has been compared. Calibration and verification of the mathematical model, with accounting for the flow breakaway of medium from the side of projectile, are achieved by using non-trivial control experiments. Analysis of stability in small criteria for the rectilinear projectile motion and calculations of the stability in large and of curvilinear trajectories have been made. A qualitative analysis of the dynamic system in the case of rectilinear motion of elongated body by inertia in the medium with accounting for its rotation around the axis of symmetry is drawn.

Dispersive behavior of waves in pre-stressed imperfectly bonded compressible elastic layered composites **11567** Tue·14:20·3

Anil Wijeyewickrema† and Sasikorn Leungvichcharoen
Tokyo Institute of Technology, Japan†

The dispersive behavior in-plane of time-harmonic waves propagating in a pre-stressed symmetric layered composite with imperfectly bonded interfaces is considered. The bi-material composite consists of compressible isotropic elastic materials. The shear spring type resistance model employed to simulate the imperfect interface can accommodate the extreme cases of perfect bonding and a fully slipping interface. The dispersion relations for both symmetric and anti-symmetric waves are obtained by formulating the incremental boundary value problem. The asymptotic behavior at low and high wavenumber limits are discussed. For numerical examples, either a compressible two-parameter neo-Hookean material or a compressible two-parameter Varga material is assumed. The effect of the imperfect interface is clearly evident in the numerical results.

Thermoacoustic effect in thin plates with residual stresses **10020** Tue·14:25·3

Ching-Chung Yin† and Shih-Ming Hsu
National Chiao Tung University, Taiwan†

A promising nondestructive inspection method based on response of thermoacoustic waves is presented to measure residual stresses in the vicinity of an intensity-modulated CW laser spot on a thin film structure. Thermoacoustic response is sensitive to the mechanical stress applied to specimen if loading direction is parallel to the direction of wave propagation. The attenuation spectrum of each plate mode has its own minimum at a specific frequency except fundamental antisymmetric mode. It is never found in photoacoustics literature. The amplitude and phase spectra in the vicinity of the specific frequency are feasible to distinguish principal values and directions of residual stresses and explored in copper thin film specimen.

An experimental study of plate wave diffraction tomography

11939
Tue·14:30·3

Andrew Rohde† and Martin Veidt
Commonwealth Scientific and Research Organisation, Australia†

This paper presents sample image reconstruction results from laboratory experiments in quantitative non-destructive evaluation of flat isotropic plates using plate wave diffraction tomography (PWDT). First, the details of a far-field reconstruction equation are reviewed, which makes use of scatter field directivity measurements to recover a low-pass filtered image of four scalar functions which describe the spatial variation of material properties within the damage region. Next, laboratory measurements of plate wave scattering for cylindrical damage obstacles of varying size and severity are used as system inputs for the image reconstructions. The results demonstrate both the quantitative performance and measurement efficiency of far-field PWDT to quantitatively recover 1) the damage size / geometry and 2) the material variations within the damage region. Hence an improved understanding of PWDT for quantitative damage detection is achieved.

Energy dissipation study for drop test of landing gear

10124
Tue·14:35·3

Jerzy Malachowski† and Wieslaw Krason
Military University of Technology, Poland†

The FEM model of the landing gear was applied to determine efforts of structural elements while simulating the landing-gear drop, and to investigate how the energy of such a system changes; also, to find what kinds of deformations occur in individual components, and to investigate into the effectiveness of the damping system. The performed crashworthy analysis for a drop test of landing gear clearly showed that the major part of vertical-fall energy is consumed by hydropneumatic shock strut and by structure. Additionally, a part of energy is dispersed in structural joints because of stick friction. Results gained from the simulation have proved how effective the 3D numerical model is and how many problems can be solved in the course of only one numerical run, e.g. the geometric and material non-linearities, the question of contact between mating components, and investigation into the problem of dissipation of energy in the whole system.

Three-dimensional reflection and refraction of seismic waves in highly anisotropic media

10218
Tue·14:40·3

Amares Chattopadhyay† and Pato Kumari
Indian School of Mines University, India†

The reflection and refraction phenomena of three dimensional plane waves at an interface between two half-spaces composed of triclinic crystalline material is considered. Closed form expressions are obtained for the reflection and refraction coefficients of qP, qSV, qSH waves in triclinic media. Also the closed form solution of the phase velocities of the qP, qSV and qSH waves are obtained. The results of the graphs are presented for different polar angle and azimuth.

Far-field solution of SH-wave by circular lining and linear crack

10796
Tue·14:45·3

Hongliang Li† and Diankui Liu
Harbin Engineering University, China†

Circular lining is used widely in structure design. In this paper, the method of Green's function is used to investigate the problem of far field solution of circular lining and linear crack impacted by incident SH-wave. Firstly, a Green's function is constructed, which is a fundamental solution of displacement field for an elastic space possessing a circular lining while bearing out-of-plane harmonic

line source force at any point; Secondly, in terms of the solution of SH-wave's scattering by an elastic space with circular lining, anti-plane stresses which are the same in quantity but opposite in direction to those mentioned before, are loaded at the region where the linear crack is in existent actually; Finally, the expressions of displacement and stress are given when the circular lining and linear crack exist at the same time. Then, the far field of scattered wave is studied. The results can be applied in the study of fracture, and undamaged frame crack detection.

Calculation collisions by using inverse method

10021
Tue·14:50·3

Janis Viba
Riga Technical University, Latvia

The indirect collisions calculation method for rigid bodies is offered. The main idea of method is that in tasks of synthesis may be found out special initial conditions before collision, provided desirable motion after collisions. They are solved symbolically or numerically using Mathcad. As a result area of special initial conditions is obtained and 3D graphics will be designed. Additional collision in plane translation motion of two rigid bodies is investigated.

Asymptotic analysis of linear wave propagation in and free vibrations of elastic helical springs

10853
Tue·16:00·10

Sergey Sorokin
Aalborg University, Denmark

Helical springs serve as vibration isolators in virtually any suspension system. A variety of theories to describe dynamic behaviour of these structural elements, which involves interaction of flexural, torsion and longitudinal waves, can be found in literature. Alongside, various approximate methods are employed to determine eigenfrequencies of vibrations of springs. The present paper contains rigorous asymptotic analysis of exact dispersion equation with two small parameters being employed. It allows identification of significant regimes (dominant balances) of wave motion in a helical spring. This analysis simplifies calculations of eigenfrequencies by means of boundary integral equations method and identification of mode shapes of helical springs. Dispersion curves and eigenfrequenices obtained by means of the proposed methodology are compared with numerical results reported in the literature.

Modelling of explosion damage tolerance in advanced space structures subject to hypervelocity impact in microgravity

11912
Tue·16:20·10

Andrew Litchfield[†] and Javid Bayandor
Royal Melbourne Institute of Technology, Australia[†]

By employing Smooth Particle Hydrodynamics, it is aimed to create a robust methodology to model hypervelocity impact (HVI) events that can provide necessary insights into the damage mechanics of HVI. The focus has been given to the formation, propagation and evolution of explosive multi-phase debris clouds formed during such impacts.

Plasticity-damage versus anisotropic damage for impact on concrete structures

11147
Tue·16:40·10

Marion Chambart,† Rodrigue Desmorat, Fabrice Gatuingt, Daniel Guilbaud and Didier Combescure
École Normale Supérieure de Cachan, France†

Impact problems on reinforced concrete (RC) structures are usually computed with models coupling plasticity and isotropic damage. The time dependency is introduced by using viscosity for two kinds of modelling: a) plasticity-damage b) anisotropic damage. Anisotropic damage described by a second order tensor has proved relevant to reproduced the quasi-static behaviour of concrete structures, based on Mazars idea that damage evolution is governed by the positive extensions. A visco- or delay-damage is introduced in tension to reproduce the strain effect experimentally observed. As long as confinement remains weak this modelisation is an alternative to complex plasticity-damage models to deal with impact problems. Only 7 material parameters are introduced (including elasticity). The efficiency of such an approach is proved by comparing the results of 3D impact computation on RC beams.

The dynamics of pizza tossing

11175
Tue·17:00·10

Kuang-Chen Liu,† James Friend and Leslie Yeo
Monash University, Australia†

We investigate a variation of the classic bouncing ball problem where the ball is replaced with a disc (pizza dough) and the platform with which the disc interacts (pizza maker's hand) undergoes a combined angular and linear oscillation along the vertical axis (pizza tossing action). In addition to the act of pizza tossing, the vibro-impact system described above also applies to a class of standing-wave ultrasonic motors, which operates by tossing the rotor at rates above 20 kHz. Through numerical simulations, we investigate the performance of different pizza tossing techniques by varying the amplitude ratio (L) and the phase lag (θ) between the vertical and rotational component of the oscillating platform. Our results show that the energy efficiency and the rotational speed are maximized when $L \simeq 1$, and $\theta = 0$.

On Hayes waves

11111
Tue·17:20·10

Philippe Boulanger
Universite Libre de Bruxelles, Belgium

Inhomogeneous plane waves are described in terms of two complex vectors, the slowness and amplitude bivectors. Here, longitudinal circularly polarized inhomogeneous plane waves are called “Hayes waves”. For these, the slowness and amplitude bivectors are isotropic and parallel, hence lie in the same plane, the polarization plane. In various contexts, we analyze the possibilities for Hayes waves to propagate for any prescribed polarization plane. The simplest case is that of incompressible isotropic linear elastic materials. Next, linearly elastic crystals with appropriate restrictions on the elastic stiffnesses are presented. There are however, in general, two exceptional polarization planes for which Hayes waves degenerate into “Hayes static solutions”. Further, it is shown that electromagnetic Hayes waves are possible for any polarization plane in electrically or magnetically anisotropic crystals, or in photoelastic materials subjected to small strain.

A new concept of dynamic biaxial plastic crushing of metallic thin-walled tubes

11086
Thu·11:00·4

Akrum Abdul-Latif† and Rachid Baleh
Université Paris 8, IUT de Tremblay, France†

A new experimental device (the ACTP: Absorption par Compression-Torsion Plastique) for the complex dynamic plastic buckling of tubes is developed generating a biaxial loading path (combined compression-torsion) from a uniaxial loading to improve the energy absorbed. Two metallic tubes made form copper and aluminum are investigated. The results show that the higher biaxial loading complexity provided by the ACTP is applied; the greater is the energy absorbed by the copper and aluminum structures. Thus, the enhancement in the energy absorption notably for the aluminum tubes, due to the highly oriented textured morphology with the presence of few dislocation cells structures and sub-structures, is higher than 150%, for the most complicated loading path compared to the uniaxial case.

Surface waves in phononic crystals with large acoustic mismatch: band structure analysys by wavelet method

10687
Thu·11:20·4

Yue-Sheng Wang,† Chuanzeng Zhang and Zhi-Zhong Yan
Beijing Jiaotong University, China†

A wavelet-based method is developed to calculate the band structures of surface modes in two-dimensional phononic crystals with large acoustic mismatch. The defect modes of the surface waves are also calculated by using the supercell technique. Re-computing the samples already studied in literatures by the present method shows its some merits. Numerical results for various systems show that the acoustic mismatch plays an important role in propagation of surface wave modes. For the cases with small acoustic impendence ratios, surface modes can propagate in almost all directions. With the acoustic impendence ratio increasing to a larger value, the appearance of SAWs becomes more difficult. For the systems with very large acoustic mismatch, only PSAW modes exist. For the systems with band gaps, the localized point-defected modes and the guided line-defected modes of SAWs or PSAWs may appear within the band gaps.

Measurements of Lamb wave band gaps and guided waves in air/silicon phononic plates and channels

11099
Thu·11:40·4

Tsung-Tsong Wu,† Wei-Chih Kuo and Jin-Chen Hsu
National Taiwan University, Taiwan†

Complete acoustic band gap of Lamb waves in a two-dimensional air/silicon phononic plate is studied theoretically and experimentally. On utilizing the interdigital transducers to launch acoustic waves, transmissions of the excited Lamb waves with frequencies below, within, and above the complete Lamb-wave band gap propagating through the phononic plate are measured and demonstrated the existence of the complete band gap. Furthermore, based on the measurements of the complete band gap, a 3-row-wide phononic channel in a silicon plate is fabricated. Lamb-wave modes with frequencies in the complete/directional band gaps propagating through the phononic plate along the channel are experimentally observed.

Experimental study on negative effective mass in a 1D mass-spring system

11577
Thu·12:00·4

Gengkai Hu,† Shanshan Yao and Xiaoming Zhou
Beijing Institute of Technology, China†

A mass-spring system with negative effective mass is experimentally realized, and its transmission property is examined in the low-frequency range. The negative effective mass is confirmed by experiment through the transmission properties of a finite periodic system. In the negative mass range, low transmissions of the system are observed and it is well predicted by the theory. In addition, zero effective mass is discussed and experimentally investigated, it implies no phase shift in the system. Finally, the anti-vibration effect with a negative mass system is also analyzed. The relevant results are helpful for better understanding the resonant nature of metamaterials.

Use of magnesium for lightweight and crashworthy S-frame

10436
Thu·12:20·4

Parisa Tehrani† and Mousa Nikahd
Iran University of Science and Technology, Iran†

Car body lightweighting and crashworthiness are two important objectives of car body design and improvement. In this task a new design of a simplified front side rail structure of an automobile body made of two different materials, or a hybrid S-frame is developed. In terms of the energy absorption and weight efficiency, the new hybrid S-frame containing aluminium or magnesium shows dramatic improvements over the conventional S-frame made of steel alloys. It is shown that a hybrid S-frame made of steel and magnesium shows the best feature from the point of view of passenger safety and weight efficiency.

The role of nonequilibrium in Hugoniot of a porous material

11131
Thu·14:00·1

Anatoly Resnyansky
Defence Science and Technology Organisation, Australia

The paper analyses the influence of non-equilibrium in a shock wave under compression of a porous material upon the Hugoniot. The Hugoniot abnormality seen as pressure rise along with a density drop observed for highly porous metals is analysed with a two-phase approach. A constitutive model, which takes into account the heat transfer exchange between phases, is used for analysis of the shock wave structure. The numerical analysis reveals several transition zones in the wave associated with equilibrating pressure and temperature. Using the model assumptions and Rankine–Hugoniot relations for the phases, the apparent abnormality is explained and a good correlation with available experiments is demonstrated for a porous copper with porosity of $m = 4$ where m is the ratio of the solid phase density to the density of the porous material.

Normal wave propagation in a rectangular elastic waveguide

10932
Thu·14:05·1

Anastasiya Bondarenko
Kiev National Taras Shevchenko University, Ukraine

The problem of normal wave propagation in a rectangular elastic waveguide is investigated based on the method of superposition. The solution obtained allows satisfying the free boundary conditions as well as the governing differential equations and calculating dispersion curves corresponding to real, imaginary, and complex propagation constants for four types of modes, existing in a waveguide of arbitrary rectangular cross-section, with any desired degree of accuracy. Discussion of the dispersion of harmonic waves is limited to a waveguide of square cross section. Frequency spectra for two types of longitudinal modes are given, and main characteristics for each dispersion branch are established.

Repeated impact between two flexible rods **10789** Thu·14:10·1

Ali Tian† and Xiaochun Yin
Nanjing University of Science and Technology, China†

The repeated impact between two flexible rods was solved by a fully continuous model based on the St. Venant's rod theory. The theoretical solutions for impact phase and separation phase are solved by the expansion of transient wave modes in a series of eigenfunctions, respectively. The impact-induced transient wave effect was considered in the solutions. The numerical results illustrate that the solutions are convergence to the number of wave modes and the time step length. Hence, the complicated impact force response including thousands of impact and separation phases and some so called "sub/micro-impact" phases can be calculated. In addition, the long-term systematic responses, such as the displacement responses of the impact interfacial surface, can be calculated as well although they are more and more complicated due to the repeated impact-induced transient waves and the alternation of impact phase and separation phase as the number of impact increases.

Effects of micro-structures on the in-plane dynamic crushing of lattice materials **11220** Thu·14:15·1

Ying Liu† and Xin-chun Zhang
Beijing Jiaotong University, China†

The influence of material micro-structures on the in-plane dynamic crushing of lattice materials is studied by means of explicit dynamic finite element simulation. Firstly, the influence of cell shapes and micro-arrangements on the specimen performance is numerically analyzed. Then the effects of defect inhomogeneous distribution on the full-scale in-plane crushing of the specimen and its micro-topology transformation are discussed. The results show that cell micro-connectivity, micro-arrangement pattern, and micro-defect location have great influence on the performance of the materials. The plateau stresses are increasing with the impact velocity, but decreasing with the missing rate, which is highly influenced by the defect location. The empirical equations for lattice materials filled with different cells and micro-arrangements at high impact velocities are formulated in terms of impact velocity, cell geometrical and topology parameters.

Study on the structure health monitoring based on AE and SMI technology **11179** Thu·14:20·1

Ying Luo† and Ziping Wang
Jiangsu University, China†

The pleiotropy of the concrete and the complicated mechanics properties make NDE of the concrete structures difficult. A series of prestressed concrete beams were loaded in three points bending until failure. The waveform acoustic emission (AE) signals were recorded and analyzed by spectral analysis and Hilbert-Huang transform. The concrete structures with different types of embedded cracks are tested by multi-actuator/sensor technology—Stack migration imaging (SMI) technology. Combined with the new-type AE technique, which uses the orthotropic piezoelectric composite material (OPCM) transducers, the SMI technology is applied to the engineering structure health monitoring. With the OPCM units, the interference of echo signals from the boundary of the concrete structures is avoided effectively. The results of experiments show that this method can reveal the characteristics of the real-time damage process of structure and the SMI technology can realize identification of the cracks.

Studies on the dynamic behavior of aluminum alloy foams

10463
Thu·14:25·1

Hongwei Ma,[†] Guitong Yang, Longmao Zhao and Zhihua Wang
Jinan University, China[†]

The compressive deformation behavior of open-cell aluminum foams with different densities and morphologies was assessed under quasi-static and dynamic loading conditions. High strain rate experiments were conducted using a split Hopkinson pressure bar technique at strain rates ranging from 500 to 2000s^{-1}.The inverse analysis is used to correct the errors that transverse inertial effect and the disperse effect of the large diameter cause. The experimental results shown that density is the primary variable characterizing the modulus and yield strength of foams and the cell size appears to have a negligible effect on the strength of foams. It also is found that yield strength and energy absorption is almost insensitive to strain rate, over a wide range of strain rates and deformation is spatially uniform for the open-celled aluminum foams.

Experimental analysis on lower clamp bolt of motorcycle front fork during frontal impact

12001
Thu·14:30·1

Shaw Wong
Malaysian Institute of Road Safety Research, Malaysia

This paper is focused on the strength integrity inherent in the front fork setup, specifically the structural strength provided by the clamp bolts between the inner tube and the stem base. As to reflect the present market scenario on the availability of both OEM and non-OEM grade clamp bolts, tests are carried out to determine the crashworthiness and therefore the level of safety it provides to consumers in their daily commuting needs.

SM10 :: Material instabilities

Chairs: Ahmed Benallal (France) and Rene de Borst (Netherlands)

Thu	14:00–14:45	Room 4	Seminars

Effects of energy-providing components in 2D discrete structures

10172
Thu·14:00·4

Yun-Che Wang
National Cheng Kung University, Taiwan

Development of high damping and high stiffness composites is of scientific and industrial importance. It has been shown that energy-providing components, such as pre-buckled elements or materials in the vicinity of their solid-solid phase transformation, may enhance overall viscoelastic properties, such as stiffness and damping, of composite materials. The energy-providing components have negative stiffness, and tend to be unstable. Here, a discrete two dimensional structure with hexagonal geometry is adopted to model the behaviour of a two phase composite material, whose inner core may consist pre-buckled elements. Both ultra high and low effective stiffness states can be obtained via tuning the amount of negative stiffness. The Lyapunov stability analysis shows that the regime that the overall stiffness peak is metastable, and the degree of the metastability depends on viscosity in each of the components. The methodology used here may be extended to analyze three-dimensional systems.

Material stability conditions for a class of inhomogeneous anisotropic media

10405
Thu·14:05·4

Carlos Daros
University of Campinas, Brazil

In the present work we analyze the hyperbolicity of a non-homogeneous differential operator of constant coefficients, which describes a class of inhomogeneous anisotropic media. This class of inhomogeneous media requires constraints on the types of material profiles. We identify two subclasses, Case A, which requires additional material constraints and Case B. We show that for Case A, the non homogeneous differential operator is hyperbolic independent from the strictly or non-strictly hyperbolic behaviour of its principal part. For Case B we have identified two regions of material instability when the operator's principal part ceases to be strictly hyperbolic. The analysis is exemplified for inhomogeneous transversely isotropic media.

Stability of an inverted spring pendulum driven by a periodic force

10730
Thu·14:10·4

Moshe Gitterman
Bar-Ilan University, Israel

There are two extensively studied ways to stabilize an inverted pendulum: the rapid vertical oscillation of the suspension axis (parametric resonance), and inserting a spring in the rod (spring pendulum). We combine these two methods and perform an analytical and the comprehensive numerical analysis of the problem. We have discovered several new effects such as the resonance between the external and oscillatory frequencies, the different influence of an external field on the elastic and oscillatory modes, and the appearance of limit cycles oscillations of finite amplitude.

Numerical modelling of strain localization in glassy polymers recognising their intrinsic anisotropy

11613
Thu·14:15·4

Huaxiang Li[†] and Paul Buckley
University of Oxford, UK[†]

An explicit numerical scheme based on the Finite Element Method (FEM) is developed, for implementing a Glass-Rubber constitutive model for amorphous polymers in solid state that recognises Intrinsic Anisotropy (GRIA model). This aims to capture the development of anisotropy of amorphous polymers arising from molecular orientation. Additional features of the model are pronounced strain-softening (de-ageing), hardening and time/temperature dependences observed in amorphous polymers. In order to implement the model in finite element analyses, a numerical solution has been developed, incorporating several numerical approaches (an iterative technique with explicit integration formulation and super-plasticity technique for very large deformations). Necking, as a typical failure mode, has been numerically simulated in polystyrene using FEM. In this way, the occurrence and nature of strain-localisation during large deformations of glassy polymers has been studied numerically.

Threshold behavior of Riemann curvature in non-euclidean continuous medium

10887
Thu·14:20·4

Tatiana Nizkaya,[†] Mikhail Guzev and Mikhail Galanin
Keldysh Institute for Applied Mathematics RAS, Russia[†]

In this paper a geometrical extension of the classical elastic medium model is considered. An additional thermodynamic state parameter is the Riemann curvature characterizing the internal interaction between the continuum particles. For this new parameter a transfer equation is constructed. The model is investigated in a simplified plain-strain set-up. The corresponding curvature equation has the unique trivial solution in the elastic case. In an inelastic case a non-trivial solution exists when the stress exceeds some critical level. It is shown that physical nature of this effect is linked with the unstable behavior of the trivial solution to small initial perturbations which results in a non-zero curvature field. The conditions for appearance of the non-trivial solution are formulated for arbitrary domain shape and surface load distribution. The corresponding critical intensities of the external load are found numerically. The numerical procedure was based on the Newton method.

Instability of compressible elastic materials at stretching stresses

10321
Thu·14:25·4

Mikhail Karyakin
Southern Federal University, Russia

The paper presents some results on stability loss in compressible nonlinearly elastic materials at stretching stresses. The numerical scheme of the investigation of post-critical behavior of the stretching rod is described and some results of its implementation in two-dimensional case are presented. For a series of commonly used models of compressible nonlinearly elastic materials an analysis of stability loss of the non-uniform stress-strain state was performed. It is shown that the stability loss due to the stretching stresses is a reflection of both material and structural instabilities.

Mathematical theory of accreted solids and its applications

10470
Thu·14:30·4

Alexander Manzhirov
Institute for Problems in Mechanics, Russia

We construct the new mathematical theory of the mechanics of accreted or growing solids which effectively describes such technological processes as winding, concreting, polymerization, pyrolytic deposition, laser spraying, electroforming, melt solidification, crystal growth, and a large number of natural phenomena. A general nonclassical boundary value problem is stated for a growing solid. We suggest a method for solving this problem by reducing it to a sequence of classical elasticity problems. After solving a sequence of such problems, one can reconstruct the true stress-strain state of the accreted solid by the decoding formulas obtained here. We consider a series of model problems on the accretion of solids from elastic and viscoelastic materials and reveal essentially new mechanical effects typical only of accreted solids.

Onset of cavitation in compressible, isotropic, hyperelastic solids

10721
Thu·14:35·4

Oscar Lopez-Pamies
State University of New York, Stony Brook, USA

In this work, we derive a closed-form criterion for the onset of cavitation in compressible, isotropic, hyperelastic solids subjected to non-symmetric loading conditions. The criterion is based on the solution of a boundary value problem where a hyperelastic solid, which is infinite in extent and contains a single vacuous inhomogeneity, is subjected to uniform displacement boundary conditions. By making use of the second-order variational procedure of Lopez–Pamies and Ponte Castaneda (2006), we solve this problem approximately and generate variational estimates for the critical stretches applied on the boundary at which the cavity suddenly starts growing. The accuracy of the proposed analytical result is assessed by comparisons with exact solutions available from the literature for radially symmetric cavitation. In addition, applications are presented for a variety of materials including the harmonic, Blatz–Ko, and compressible Neo-Hookean materials.

Self-retracting motion and extreme anisotropy of graphite

11836
Thu·14:40·4

Quan-shui Zheng,[†] Bo Jiang, Lifeng Wang, Shoupeng Liu, Jing Zhu, Qing Jiang, Yuxiang Weng, Li Lu, Sheng Wang, Qikun Xue and Lianmao Peng
Tsinghua University, China[†]

We observed a novel phenomenon that tiny flakes of graphite, after being displaced to various suspended positions from islands of highly orientated pyrolytic graphite, retract back onto the islands under no external influences. Reports of this phenomenon have not been found in the literature for single crystals of any kinds. A critical size of flakes, approximately 3 5 m, was also observed, above which the self-retracting motion does not occur. Models that include the van der Waals interaction force, electrostatic force, static and dynamic shear strengths, and plastic deformation were considered to explain the observed phenomenon. We further found that graphite has the highest elastic anisotropic degree than those of all other hexagonal crystals. These findings may conduce to create nano-electromechanical systems with a wide range of mechanical operating frequency from mega to giga hertz.

SM11 :: Mechanics of composites

Chairs: Peter Gudmundson (Sweden) and Donatus Oguamanam (Canada)

Mon	14:00–16:00	Room 10	Lectures
Mon	16:25–17:45	Room 10	Lectures
Wed	10:40–13:00	Room 10	Lectures
Thu	14:00–14:30	Room 5	Seminars

Buckling simulation of imperfect cylindrical composite shells using Reissner–Mindlin–von Karman type shell facet model

10341
Mon·14:00·10

Petri Kere† and Mikko Lyly
Tampere University of Technology, Finland†

Designing with laminated composites requires validated simulation procedures for the buckling simulation of thin-walled cylindrical shells. Structural optimization with the undisturbed shell geometry does not lead to the optimum with realistic, geometrically imperfect shells. Bringing the initial imperfection on the shell geometry changes the order of buckling loads and thus the criticality of different stacking sequences. This presentation deals with the buckling simulation of imperfect CFRP shells under axial compression. The simulation is performed with a geometrically nonlinear analysis using Reissner–Mindlin–Von Karman type shell facet model. Typical postbuckling deformation pattern observed for the experimental test shells found in the literature is used for modeling the geometric imperfection shape and amplitude. Numerical results are compared to the experimental limits of buckling loads achieved for the geometrically imperfect cylindrical shells.

Effective properties of nonlinear power law elastic periodic composites

12175
Mon·14:20·10

Vincent Monchiet† and Guy Bonnet
Universit Paris-Est Marne la Valle, France†

A series solution to obtain the effective properties of nonlinear power law elastic composites media having periodically located heterogeneities is described. The method of solution uses the classical expansion along Neuman series of the solution of the periodic elasticity problem in Fourier space, based on the Green's tensor, and exact expressions of factors depending on the shape of the inclusions. The case of power law elastic composites induce infinite moduli when the stress tend to zero. To circumvent this difficulty, a dual expression of the formulation of the integral equation is used for the solution in the Fourier space. Comparisons with existing numerical data, available in the literature, are proposed and illustrate the relevance of the approach.

A coupled analytical model for hydrostatic response of 1-3 piezocomposites

10617
Mon·14:40·10

Nimal Rajapakse† and Chen Yue
The University of British Columbia, Canada†

Piezocomposites are made by the combination of piezoelectric ceramics with another material. Such composites can be used to maximize electromechanical coupling. The fibers (rods) of piezocomposites are made of piezoelectric materials and the matrix material is a polymer. Piezocomposites were originally developed for hydrophone applications, but have also been extended to other applications. This study presents a fully coupled analysis of a unit cell of a 1-3 piezocomposite under hydrostatic loading. The governing equations for electroelastic field of transversely isotropic piezoelectric and

elastic media are used. A reduced form of the analytical solutions expressed in terms of series of modified Bessel functions is used. The solution of the boundary-value problem corresponding to a unit cell is presented. The effective hydrostatic properties of a 1-3 piezocomposite are obtained for different fiber volume fractions, polymer and piezoceramic properties and fiber aspect ratios.

3D elastodynamics of an interface crack **10620**
Mon·15:00·10

Igor Guz,† Olexandr Menshykov and Maria Kashtalyan
University of Aberdeen, UK†

The present paper investigates the elastodynamic response of inter-component cracks in composite materials with the focus on the effect of crack closure leading to contact interaction of the opposite crack faces. In particular, application of boundary integral equations to the problem of interface microcracks between two dissimilar elastic half-spaces under harmonic loading is studied in detail. The system of linear algebraic equations is derived to solve the problem numerically. The distributions of the displacements and tractions at the interface and the crack surface are obtained and analysed. The stress intensity factors (opening and shear modes) are computed for different values of the wave frequency and different properties of the half-spaces. It is shown that the limiting cases of the obtained solution are in a very good agreement with the analytical static solution for an interface crack and with the numerical dynamic solution for a crack in the homogeneous body.

Analyses of a metallic rod bridging a unbonded interface **10902**
Mon·15:20·10

Brian Legarth
Technical University of Denmark, Denmark

Several 3D technologies (stitching, tufting, 3D weaving and Z-fibers) are currently available in order to suppress delamination cracks in laminates and composites but the material design community is still waiting for reliable models to come. The problem is generally 3D and involves plasticity, contact and debonding. However, by adopting plane strain analyzes this work consider a simplified model of a through-thickness reinforcing z-pin bridging two substrates which are subjected to relative shearing. Plasticity in the constituents of the specimen as well as debonding and contact between the z-pin and the substrates will be accounted for. The effect of different material parameters, including different orientation of the z-pin, is investigated. Stresses, plastic zones and deformations developed near the z-pin are analyzed in details in order to explained the overall average stress-strain response. The results are compared with experiments and good qualitatively agreements are found.

Damage evolution during thermo-oxidation of polymeric matrix composites **10950**
Mon·15:40·10

Kishore Pochiraju,† Gyaneswar Tandon and Greg Schoeppner
Stevens Institute of Technology, USA†

High temperature polymeric matrix composites provide the weight and performance advantages for aerospace applications and can operate in the 250–350°C temperature range. Oxidation of the resin and fiber constituents is driven by the oxygen diffusion and reaction characteristics. However, the oxidation progression in the composite material is orthotropic and driven by damage progression in the resin and at the fiber-matrix interface. This paper uses coupled thermo-chemical-mechanical analysis to simulate the progression of oxidation and evolution of damage in unidirectional and fabric reinforced composites. The oxidation induced morphological changes and shrinkage strains are modeled to determine the stress and deformation states during the life of the composite. Parametric analysis relating the oxidation and damage growth and its correlation with experimental observations are presented for selected high temperature composite systems.

Modeling of the degradation of laminates under impact: some key points

11245
Mon·16:25·10

Olivier Allix,† Jean-Mathieu Guimard and Nicolas Feld
École Normale Supérieure de Cachan, France†

The presentation is focused on some key aspects of the meso-modeling of the deterioration mechanisms of long fiber laminates under impact. The first aspect concerns the coupling between transverse crack and delamination, this coupling in fact mainly determines the damage pattern in case of low-velocity impact. The two other aspects are related to the modeling of fragmentation under dynamic compressive loading and the modeling of rate effect for delamination crack propagation. The absorption of energy under higher velocities strongly depends on a competition between those two mechanisms.

Delamination of compressed thin layers at corners

11325
Mon·16:45·10

Johan Clausen,† Henrik Jensen and Kim Sørensen
Aalborg University, Denmark†

An analysis of delamination for a thin elastic film, attached to a substrate a corner, is carried out. The film is in compression and the analysis is performed by combining results from fracture mechanics and the theory of thin shells. The results show a very strong dependency of the angle of the corner. In contrast with earlier results for delamination on a flat substrate, the present problem is not a bifurcation problem. It is asserted whether crack growth is most likely to take places in the direction parallel to the corner or in the direction perpendicular to the corner. It is found that this behaviour is very much influenced by the magnitude of frictional stress between crack faces in contact.

Multiple curved micro-beams model for in-plane mechanical properties of stitched composite laminates

11368
Mon·17:05·10

Junqian Zhang† and Yuqing Wei
Shanghai University, China†

Four meso-structural parameters such as distortion length, distortion width, minor axis and major axis of stitch hole are introduced to characterize the local in-plane fibre configuration around the stitches. A fibre distortion model (FDM) is developed based on the investigation of typical morphology to describe the in-plane fibre misalignment angle and inhomogeneous fibre content using the meso-structural parameters. A multiple curved micro-beam model considering the interaction of adjacent fibres is established. In this model the fibres are represented by curved Euler-Bernoulli beam and deform in both axial extension and in bending. Two failure modes such as fibre fracture and matrix shear failure are considered. The tensile failure process is simulated using the unified multiple curved micro-beam model, coupling with Monte-Carlo simulation technique.

The characterization of interface adhesion of dissimilar elastic-plastic materials by a pressurized blister test modeling

11431
Mon·17:25·10

Yichun Zhou† and Limei Jiang
Xiangtan University, China†

A concept of the interface adhesion energy, has been proposed to characterize the quality of interface adhesion of the elastic-plastic materials system. A geometrically nonlinear finite element analysis of a blister test of an elastic-plastic film bonded to an elastic-plastic substrate has been conducted.

The fracture process ahead of the crack tip at the interface between the thin film and the substrate is represented in terms of a built-in cohesive model, for which interface adhesion energy and the peak stress required for separation are basic parameters. Effects on the critical pressure of various influencing parameters are studied. The plastic work in the substrate contributes significantly to the critical pressure. Agreement between modeling prediction and measurement evidences the validity of the proposed concept and the method of extracting the interface adhesion energy.

Transverse crack behavior in satin woven carbon fiber reinforced/epoxy composite laminates at cryogenic temperatures

11576
Wed·10:40·10

Shinya Watanabe,† Yasuhide Shindo, Tomo Takeda and Fumio Narita
Tohoku University, Japan†

The objective of this research is to investigate the crack behavior in five harness satin woven carbon fiber reinforced polymer (CFRP) composite laminates with temperature-dependent material properties under tension at cryogenic temperatures. Cracks are assumed to have occurred in the transverse fiber bundles, and both cases where the tips of the cracks are located in the fiber bundles or at the interfaces between two fiber bundles are considered. The stress singularity at the interface tip of the crack is determined. A finite element technique utilizing special singular elements is used to obtain the stress intensity factors at the tips of the transverse cracks in two-layer woven CFRP laminates, and the results are discussed in detail. The results from this study will be useful in understanding the cryogenic behavior of the transverse fracture in the woven CFRP laminates, which are candidate materials for fuel storage systems used in space vehicles.

Micromechanics-based nonlocal modeling of elastic matrices containing aligned spheroidal inclusions

11409
Wed·11:00·10

Ilaria Monetto† and Walter Drugan
University of Genoa, Italy†

A micromechanics-based nonlocal constitutive equation relating the ensemble averages of stress and strain for a matrix containing a random distribution of non-spherical hard inclusions having macroscopic transversely-isotropic behavior is derived. The model of impenetrable particles considered consists of identical spheroids having aligned orientations. The analysis builds on and generalises previous papers where elastic composites containing spherical and randomly oriented spheroid-shaped inclusions were analysed. In particular, it is shown how the task of the statistical description of the microstructure can be make reasonable by performing a simple scale transformation. The new constitutive equation is then used to explore nonlocal effects of shape and spatial distribution of inclusions on the anisotropic response of the composite.

The effect of interfaces on the plastic behavior of periodic composites

10642
Wed·11:20·10

Martin Idiart† and Norman Fleck
University of Cambridge, UK†

Homogeneization estimates are given for predicting the effect of microstructural size on the strength of multi-phase periodic composites. It is assumed that the strength is elevated by plastic strain gradients in the bulk and by the resistance to plastic slip at internal material interfaces. Sample results are shown for a two-phase, power-law material with a cubic array of spherical reinforcement particles. The macroscopic stress-strain relations are found to exhibit Hall–Petch behavior, and the size effect becomes more pronounced with increasing interface strength. Moreover, size effects are predicted for both yield strength and plastic hardening rate of the composite. The relative magnitude of these two effects is sensitive to the choice of constitutive description of the interface.

Free edge effects of thermoplastic composite laminates

11183
Wed·11:40·10

Min Shen,† Hongqi Li, Shibin Wang and Jingwei Tong
Tianjin University, China†

The interlaminar deformation on the free edge surface in thermoplastic composite AS4/PEEK laminates are measured by the of microscopic moire interferometry under uniaxial tensile loading. A fully three-dimensional orthotropic elastic-plastic finite element analysis of the interlaminar stresses and deformation are carried out for the laminates. The numerical tensile stress-strain curves, interlaminar displacement and shear strain simulated by FE models are consistent with the experimental corresponding results. Three-dimensional distributions of the elastic-plastic interlaminar stresses and deformation of this kind laminate are predicted by means of the present FE model which considers the ductility of PEEK matrix.

Continuum analysis for a unidirectional composite with a penny shaped crack

10893
Wed·12:00·10

Michael Ryvkin† and Jacob Aboudi
Tel Aviv University, Israel†

The three dimensional problem of a periodic unidirectional composite with a penny shaped crack traversing one of the fibers is analyzed by the continuum equations of elasticity. By employing the representative cell method, based on the triple discrete Fourier transform, the original problem for the infinite two-phase composite space is reduced to a problem for a finite size representative cell, formulated with respect to the transforms of the elastic field variables. This problem is solved by using the higher-order theory. The obtained accurate stress distribution allowed the introduction of the *point stress concentration factor*, a new accurate strength characteristic of the composite with a broken fiber, defined by the maximal stress in the first intact one. It is shown that the traditional use of the average stress in the first intact fiber for the composite strength prediction may lead to significant overestimation.

On modelling reinforced composites exhibiting stochastic uncertainties on volume fraction: a stochastic micromechanical approach

10821
Wed·12:20·10

Johann Guilleminot,† Christophe Binetruy, Djimédo Kondo and Christian Soize
Ecole des Mines de Douai, France†

Many materials exhibit uncertainties on their macroscopic properties. This basically results from random fluctuations observed at lower scales, especially at the mesoscale where microstructural uncertainties generally occur. In this study, we propose a theoretical stochastic framework in which the volume fraction at the microscale is modelled as a random field whose reduction is performed using a Karhunen–Loeve expansion. An experimental procedure dedicated to the identification of the parameters involved in the probabilistic model is also presented and relies on a non-destructive ultrasonic method. The methodology is then applied to a long fiber thermoplastic. It is shown that the volume fraction can be modelled by a homogeneous random field whose spatial correlation lengths are determined and may provide conditions on the size of the mesovolumes to be considered. The impact of such volume fraction random fluctuations on the stochastic overall properties is also investigated.

Transient response of active constrained-layer damped FGM beams **11238** Wed·12:40·10

Donatus Oguamanam† and Elena Miroshnichenko
Ryerson University, Canada†

A typical active constrained-layer damping beam system comprises three layers. The beam is the bottom layer and it is made from isotropic materials, a viscoelastic material forms the middle layer, and a constraining layer (i.e., top layer) that is often made from a piezoelectric material which acts as an actuator. Often piezoelectric layer is included between the beam and the viscoelastic layer to act as a sensor. The transient response of such systems is investigated in the present study for the case of beams which are made of functionally graded material (FGM). The constraining layer is a piezoelectric fibre-reinforced composite (PFRC) laminate. A quasi-2D finite element formulation is employed in the derivation of the discretized governing equations. The effect of stacking sequence, lay-up, boundary conditions, and the variation of the elastic modulus of the beam are examined.

Micromechanism of deformation in EMC laminates **10544** Thu·14:00·5

Zhengdao Wang
Beijing Jiao-Tong University, China

Elastic memory composite (EMC) materials are receiving more attentions in deployable spacecraft industry because they can realize much high packaging strains without damage and automatically recover to their original shapes when subjected to a specific thermomechanical cycle. Experimental results have confirmed that microbuckling and post-microbuckling responses of compressed fibers in the soft matrix are the primary deformation mechanism for EMCs to realize high packaging strains than traditional composites. However, a thorough understanding about the deformation mechanics of EMCs has not yet been achieved. This paper presents a new shear/tension microbuckling solution to explore the micromechanics of EMC laminates under bending. The microbuckling wavelength of carbon-fiber/resin EMC laminates were calculated and compared with the experimental observation.

Thermo-mechanical constitutive laws for particle-reinforced composites including multi-type ellipsoidal reinforcements **10704** Thu·14:05·5

Yasser Shabana
El-Mataria, Masaken Elhelmia, Egypt

While composite materials are defined as a mixture of two or more different materials, many research works dealt with composites of two constituents in the literature. On the other hand, the research works that dealt with more than two constituents are rare. Since Suitable amount of additives as sintering aids, in the sintering process for example, could lower the sintering temperature and improve the interlaminar fracture resistance, it is important to develop the constitutive laws for this class of composites. Therefore, the aim of this paper is to propose constitutive laws that predict the thermo-mechanical behavior of composites with multi phase ellipsoidal inclusions. This includes particles with different materials and/or different shapes (aspect ratio). These constitutive laws predict the thermomechanical macroscopic and microscopic behaviors as well as characterize the overall properties such as modulus of elasticity, Poisson's ratio and thermal expansion coefficient.

Meso-mechanical investigation on high temperature oxidation of thermal protective ceramics

11896
Thu·14:10·5

Jun Liang,† Chao Wang and Yang Liu
Harbin Institute of Technology, China†

By the investigation on the phase transformation mechanism of ZrB_2+SiC thermal protective ceramics in ultra-high temperature ambient, characteristics of phase transformation during oxidation and laws for high temperature mechanical performance of constituent material have been analyzed by Eshelby's equivalent inclusion theory. By the principle of mass conservation and volume conservation of solid phase, cavity nucleation and evolution in SiC depletion layer have been investigated. Considering interaction between cracks and solid phase, the relation of microstructure and macroscopic property of ZrB_2+SiC composites has been predicted and calculated numerically. The results show that the volume expansion of resultant phase and the volume fraction of SiC are the major factors leading to the cavity nucleation and evolution in SiC depletion layer. The Young's modulus increases in inverse proportion to the growth of cracks, resultant phase and volume fraction of SiC.

Influence of imperfect elastic contact condition on the effective properties of piezoelectric fibrous composites

11885
Thu·14:15·5

Federico Sabina,† Reinaldo Rodriguez-Ramos, Juan Lopez-Realpozo,
Raul Guinovart-Diaz and Julian Bravo-Castillero
Universidad Nacional Autonoma de Mexico, Mexico†

A fiber-reinforced periodic piezoelectric composite where the constituents exhibit transverse isotropic properties, is considered. The fiber cross-section is circular and the periodicity is the same in two directions. Imperfect mechanic contact conditions at the interphase between the matrix and fibers are represented in parametric form. In order to analyze the influence of the imperfect interface effect over the behavior of the composite, the effective axial piezoelectric moduli are obtained by means of the Asymptotic Homogenization Method. Some numerical examples are given.

The influence of the dimension ratio and interfacial debonding on plastic flow of cylindrical SiC reinforced aluminum matrix composites

11835
Thu·14:20·5

Ying Zhang† and Shaoxing Qu
Zhejiang University, China†

Second phase reinforced metal-matrix composites (MMCs) have attracted researchers across fields of materials and mechanics for over 50 years. Volume fraction, shape, size of the second phase all contribute to their reinforcement effect. In this study, we focus on one special shape, namely, cylindrical, of SiC as the reinforced phase, and aluminum as the metal matrix. A widely-used cohesive zone model, as well as a perfectly connected interface, is adopted to account for the interfacial interaction between the reinforced phase and the matrix interface. With the same volume fraction of SiC, different dimension rations are studied numerically to obtain the stress-strain relation of the SiC reinforced aluminum matrix materials.

Accurate modelling of FRP composite sandwich plates having interlaminar slips

11275
Thu·14:25·5

Anupam Chakrabarti
Indian Institute of Technology, Roorkee, India

FRP composite sandwich plates provide unique solution where weight minimization is one of the major concerns.The most important feature of laminated plate is that it is comparatively weak in shear. This phenomenon is quite significant in case of sandwich plates due to wide variation of material properties between core and faces. As such the effect of shear deformation should be incorporated in the analysis in a proper manner. The analysis of laminated FRP sandwich plates becomes further complex if interlaminar slips are observed. In this study an accurate finite element model is reported based on refined higher shear deformation theory and a linear spring layer model to represent the behavior of laminated FRP composite sandwich plates having interlaminar slips with reasonable computational efficiency.

SM12 :: Mechanics of phase transitions

Chairs: Kaushik Bhattacharya (USA) and Erik van der Giessen (Netherlands)

Tue	10:40–12:40	Room 8	Lectures
Thu	14:50–15:00	Room 2	Seminars
Fri	09:15–10:35	Room 8	Lectures

Virtual melting as a mechanism of crystal-amorphous and crystal-crystal phase transformations and plastic relaxation

10936
Tue·10:40·8

Valery Levitas
Texas Tech University, USA

A new mechanism of temperature and pressure-induced crystal-amorphous and crystal-crystal phase transformations (PTs), as well as plastic relaxation via virtual melting (VM) significantly below (100-1000K) the melting temperature is justified thermodynamically and kinetically. It is found that the nonhydrostatic stresses, induced during solid-solid PT or by external loading, may cause melting. Immediately after the melting, the stresses relax and unstable melt solidifies. Developed thermodynamic and kinetic approaches are applied to interpretation of beta-delta PTs in HMX explosive, as well as to pressure-induced crystal-crystal PT and amorphization in geological (ice, quartz, coesite), electronic (Si and Ge), and superhard (C and BN) materials. Some indications were found that VM may serve as mechanisms of plastic flow under high-strain-rate and shock loading of HMX, metals, and metallic nanowires; fracture; nanofriction; sublimation; and grain growth and sliding.

Multi-phase-field recrystallization simulation based on deformation microstructure

10636
Tue·11:00·8

Tomohiro Takaki† and Yoshihiro Tomita
Kyoto Institute of Technology, Japan†

We developed a static recrystallization model which enables natural nucleation and grain growth from deformation microstructure. In this model, the subgrain microstructure at large deformation is predicted from crystal orientation and stored energy calculated by crystal plasticity finite element simulation. The nucleation and growth of recrystallized grains from the predicted microstructure is simulated by multi-phase-field method with computationally efficient algorism. From the results of simulation employing the developed model, we could confirm that the proposed model can reproduce the plausible recrystallization process.

Nucleation and growth of stress-induced martensitic fine layered structures in shape memory alloys under uniaxial tension

11542
Tue·11:20·8

Yongzhong Huo,† Cheng Peng and Yan Yan
Fudan University, China†

Through image analysis of fine layered microstructures of CuAlNi single crystalline shape memory alloys under uniaxial tension tests, a phase character function, 1 for martensite and 0 for austenite, was obtained at several preselected loads. Since no periodicity could be detected, certain statistical averages were performed to obtain the distributions of the phase fraction and the number of interfaces along the sample. Their evolutions indicated that the stress-induced martensitic transformation had three periods: nucleation, mixed nucleation and growth, merging due to growth. It was further found that the transition was of multi stage, i.e. the sample could be divided into several regions, in which the nucleation and growth processes proceeded quasi independently and all had the three-period character. These characteristics were further confirmed by the evolution of the average martensite band width and the total number of interfaces, which could be well fitted by some1d models.

Elastoplastic phase-field simulation of cubic-tetragonal martensitic transformation in polycrystals

11528
Tue·11:40·8

Akinori Yamanaka,† Yoshihiro Tomita and Tomohiro Takaki
Kobe University, Japan†

We propose an elastoplastic phase-field model of the cubic - tetragonal martensitic transformation with plastic deformation in a two-dimensional polycrystal using the phase-field microelasticity theory. In this model, the evolution of plastic strain during the martensitic transformation is described by the time-dependent Ginzburg-Landau equation. The simulation results shows that the proposed phase-field model can reproduce the cubic - tetragonal martensitic transformation in the polycrystalline material including not only evolution of stress-accommodating multi-variant martensitic structure from grain boundary of parent phase but also plastic deformation reducing the transformation-induced stress. Therefore, the extension of this elastoplastic phase-field model will be a useful tool predicting for the formation of the martensitic microstructure affected by self- and plastic accommodations, such as lath martensite.

Electrical induced crack propagation and domain switching in ferroelectric single crystal

11093
Tue·12:00·8

Daining Fang† and Ye-Jian Jiang
Tsinghua University, China†

In this investigation, using a designed and constructed novel experimental setup, the experiments were performed on in-situ observation of domain switching and crack propagation in thin plate pre-crack specimens of ferroelectric single crystal subjected to electric loading. The in-situ observed images indicate that under a critical field, when the crack propagates by an extension of , a pair of new 900 switched zones with the same width is induced on both sides of the crack face just behind the crack tip. To describe the experimental results, an electrically induced crack propagation model based on the first principle of thermodynamics is established. In this model, the energy relative to domain switching induced by the intensive electric field at the crack tip supplies the major thermodynamic driving force for electric-field-induced crack propagation in ferroelectrics. The theoretical critical field inducing crack propagation agreed well with the experimental one.

Micromagnetic theory of ferromagnetic shape memory alloys

11676
Tue·12:20·8

Jiangyu Li
University of Washington, USA

It is widely recognized that the rearrangement of martensite variants in a ferromagnetic shape memory alloy (FSMA) can lead to much higher strain than conventional magnetostriction. In this work, we develop micromagnetic theory to study the magnetic field induced strain in FSMA from energy minimization point of view. For single crystalline FSMA, we show that magnetization rotation can reduce ferromagnetic shape memory effect substantially when motion of the interface is severely hindered under a relatively large stress. For polycrystalline FSMA, we estimate the magnetic field induced strain from Taylor bound, and identify the optimal textures for maximum actuation strain in FSMA polycrystals of various crystallographic symmetries. In addition, we develop a novel phase field simulation that captures the variant rearrangement and magnetization rotation in FSMA simultaneously, which confirms our theoretical analysis. These results agree well with experiments.

Thermomechanical properties of shape-memory polymer and composite

10703
Thu·14:50·2

Hisaaki Tobushi,† Yoshiki Sugimoto, Yoshihiro Ejiri and Shunichi Hayashi
Aichi Institute of Technology, Japan†

The basic thermomechanical properties of polyurethane-shape memory polymer (SMP): shape fixity and shape recovery, have been investigated. These thermomechanical properties are induced based on the glass transition of the material: high rigidity at low temperature and low rigidity at high temperature. The conditions to obtain high shape fixity and shape recovery are clarified. The deformation properties of foam and the secondary-shape forming of the material are clarified. The thermomechanical bending properties of shape memory composite with shape memory alloy and SMP are also clarified. The future subjects are discussed.

Atomic-scale mechanism of crack-tip deformation: twinning and phase transformation

11020
Thu·14:55·2

Ya-Fang Guo,† Wen-Ping Wu and Lei Liu
Beijing Jiaotong University, China†

The deformation behaviour of the crack tip in bcc iron and B2 NiAl at low temperatures and high loading levels are investigated by atomistic simulations. Twinning and martensitic phase transformation have been observed for different types of crack. We have found that the combination of the local stress and crystal orientation plays an important role on the mechanism of the crack tip deformation. A simple way to determine the deformation mechanism of the crack tip region is developed, which is successfully applied in analyzing the complicated deformation behaviors of the crack tip in bcc iron and B2 NiAl.

Stress-induced martensitic phase transformation in Nitinol

10799
Fri·09:15·8

Samantha Daly,† Kaushik Bhattacharya and Guruswami Ravichandran
University of Michigan, USA†

Using the in-situ optical technique known as Digital Image Correlation (DIC), full-field quantitative strain maps of localization have been experimentally obtained for the first time in thin sheets of Nitinol. The use of DIC provides new information connecting previous observations on the micro- and macro-scales. It shows that the transformation initiates before the formation of localized bands, and that the strain inside the bands does not saturate when they nucleate. The effect of rolling texture on the macroscopic stress-strain behaviour was observed and it is shown that the resolved stress criterion does not hold for polycrystalline Nitinol. Finally, we have probed the role of geometric defects and shown that localization in SMAs is not purely a geometric instability, but a competition between material and geometric instabilities.

Guided phase pattern formation in monolayers

10816
Fri·09:35·8

Wei Lu
University of Michigan, Ann Arbor, USA

A binary monolayer on an elastic substrate may self-organize into ordered nanoscale phase patterns. Here we report a work of using a substrate strain field to guide the self-assembly process. The study shows that straining a substrate uniformly does not influence the pattern. However, a non-uniform strain field significantly influences the size, shape and distribution of self-assembled features. The study suggests a method of strain field design to make various monolayer patterns.

An elastoplastic phase field model for microstructure evolution

10897
Fri·09:55·8

San-Qiang Shi
The Hong Kong Polytechnic University, Hong Kong

Microstructure evolution is common during material processing. Since many properties of materials are determined by the microstructure of materials, in recent years much effort was made to develop computational methodologies for predicting the evolution of microstructure of materials. One of these methodologies is the phase field method (PFM). PFM describes a microstructure using a set of conserved and nonconserved field variables that are continuous across the interfacial regions. In this paper, the strain energy of a homogeneous body is presented as a function of phase field variables that include the effective stress-free elastic and plastic strains. Examples for hydride precipitation in metals will be given. Therefore, the proposed phase field model provides a tool to study the dynamic evolution of microstructures that involve plastic deformation.

Discrete dislocation-transformation model for austenitic single crystals

10914
Fri·10:15·8

Sergio Turteltaub,[†] Erik van der Giessen and Jingyi Shi
Delft University of Technology, Netherlands[†]

A discrete model for analyzing the interaction between plastic flow and martensitic phase transformations has been developed to simulate the microstructure evolution in a single crystal of austenite that transforms non-homogeneously into martensite. The plastic flow in the untransformed austenite is simulated using a plane-strain discrete dislocation model. The phase transformation is modeled via the nucleation and growth of discrete martensitic regions embedded in the austenitic single crystal. Simulations of single crystals subjected to uniaxial tension and compression indicate that instantaneously the most efficient mechanism for stress relaxation can be achieved by a combination of transformation and plastic deformation. However, these mechanisms are quickly depleted and the material experiences a strong hardening.

SM14 :: Multibody and vehicle dynamics

Chairs: Jorge Ambrósio (Portugal) and Werner Schiehlen (Germany)

Mon	14:00–16:00	Room 3	Lectures
Tue	10:40–12:40	Room 3	Lectures
Thu	14:00–14:35	Room 8	Seminars
Fri	09:15–10:35	Room 3	Lectures
Fri	11:00–12:20	Room 3	Lectures

A fast iterative solution of the wheel-rail contact

11198
Mon·14:00·3

Ingo Kaiser
German Aerospace Center, Germany

A method based on the half-space assumption is developed to calculate the stress distribution in the wheel-rail contact. Due to the shape of the profiles of wheel and rail, the widely used theories of Hertz and Kalker cannot be applied if the stress distribution within the contact is required, e.g. for analysing the wear. For the calculation, the stress distributions are discretised using a grid and local functions. By inserting the discretised distributions into the Boussinesq–Cerrutti equations, two systems of linear equations with non-linear conditions are obtained, one for the normal contact problem, the other for the tangential contact problem. The solution of the systems of equations is done iteratively by applying the Gauss–Seidel algorithm. The results obtained with this method fit very well with calculations made with Finite Element models. However, the developed method is fast enough to be integrated into the multi-body simulation of an entire railway vehicle.

Comparison of fast algorithm and FEM results for wheel-rail contact simulation

10064
Mon·14:20·3

Alexander Olshevsky† and Vladislav Yazykov
Bryansk State Technical University, Russia†

Two different approaches in wheel-rail contact simulation are discussed. The major attention is focused on the analysis of the accuracy of the contact problem solutions, which can be obtained using so-called fast algorithm. This algorithm is an approximate model of wheel-rail contact, which does not lead to stiff equations of motion and can be used for the case of bodies with non-quadratic shapes. The normal contact pressure distribution is computed using the elastic Winkler foundation model. The foundation modulus is computed using the half space method. The tangential contact problem is solved using the modified FASTSIM algorithm. Since FEM solution does imply such restrictions as symmetry of the contact patch and its small size with respect to the contacting bodies size, it can be used for the accuracy estimation. The refined FEM models are used; typical cases of the wheel-rail contact are simulated. The frictional contact problem is solved for the cases of a conformal contact.

On the contact detection for contact analysis in multibody systems

11246
Mon·14:40·3

Paulo Flores† and Jorge Ambrósio
University of Minho, Portugal†

The purpose of this work is to present a methodology to adjust the time step for the contact detection. The idea is to ensure that the first impact within a multibody system does not occur with a large value for relative bodies' penetration in order to avoid the artificially large contact forces associated.

During the numerical integration of the system equations of motion if the first penetration is below this small value previously specified, then the current time is taken as the impact time. If the first penetration is larger than the specified tolerance, then the current time step is beyond the impact time. In this case, integration algorithm is forced to go back and take a smaller time step until a step can be taken within the acceptable tolerance. Results obtained from computational dynamic simulations are used to study the validity of the methodology proposed.

Oscillation reduction of cranes by hoisting manipulation **10928** Mon·15:00·3

Edwin Kreuzer† and Andreas Bockstedte
Hamburg University of Technology, Germany†

Payload oscillations can be excited by e.g. wind loads or by displacements of support mechanisms and endanger the operation of cranes. Variable cable length during hoisting excites additional oscillations. Hence, the reduction of payload pendulations is important in crane dynamics and system design. A control strategy is presented where the desired hoisting velocity is manipulated by superposition of a suitably modulated motion in order to reduce amplifications of the pendulations. In a force-feedback loop a winch with appropriate dynamic behavior can emulate the visco-elasticity of a soft elastic pendulum. Choosing the control parameters according to the internal resonance case establishes the excitation of a controlled periodic motion along the direction of the cables, thereby, the amplitude of the pendulation is reduced. Experimental results are presented and a controller design strategy is discussed for a multibody flying crane model.

Planetary rover mobility performance on soft and uneven terrain **11243** Mon·15:20·3

Bernd Schäfer,† Rainer Krenn and Andreas Gibbesch
German Aerospace Center, Germany†

Planetary rovers with different configurations will be developed at ESA. Since mobility has to be guaranteed in rough terrain, they need extensive all-terrain locomotion capabilities. To achieve successful mission and to enhance the overall rover mobility performance, efficient simulation tools are required that cope with the wheel-soil interaction and regard the overall rover-chassis set-up based on multibody system (MBS) approach, with various kinematic suspension and wheel mobility concepts. In the field of terramechanics the interaction of a vehicle's wheels on soft soil is investigated. Physical contact modelling by: (a) using PCM (polygonal contact model on hard soil) method, and (b) SCM (soft and loose soil contact model) method. SCM provides the dynamics of a plastically deformable surface using an elevation grid description, and can favourably be applied to simulate the famous multi-pass effect. Both methods have been set up and integrated inside a multi-body simulation tool.

Smoothing friction phenomena in railway dynamics **10099** Mon·15:40·3

Werner Schiehlen,† Jens Koenig and Peter Meinke
University of Stuttgart, Germany†

Railway dynamics is characterized by the wheel-rail contact problem featuring the self-guidance of the wheelset running on the track, on the one hand, and the generation of noise and wear, on the other hand. However, in railway engineering it was observed that friction induced phenomena are less critical during cornering on rails mounted on steel bridges. One hypothesis is that the structural vibrations performed by the rails on bridges are smoothing friction. The paper presents models for the analysis of smoothing friction phenomena. A first model uses Coulomb's friction law for the wheel-rail contact resulting in a discontinuous system. In a second time-continuous model a more

realistic contact law including linear elasticity and saturation by sliding friction is applied. It turns out that high frequency motions in the contact patch produce pure sliding smoothing the friction phenomena while the guidance of the wheelset is achieved by stiffness within the railway bogie, respectively.

Measurements and simulations or rail vehicle dynamics with respect to overturning risk

10456
Tue·10:40·3

Dirk Thomas† and Mats Berg
Royal Institute of Technology, Sweden†

Rail vehicles are exposed to strong lateral influences through curves, track imperfections and crosswind leading to large deflections of the vehicle suspension systems. In recent years an increased interest in building lighter rail vehicles aiming less energy consumption has emerged. However, building lighter vehicles increases the sensitivity of the vehicles to crosswind and thus the risk of overturning. In the present work quasi-static and dynamic multibody simulations in 2D and 3D are performed in order to study the influence of suspension modelling on vehicle overturning risk. Suspension deflection measurements in lateral direction between carbody and bogies on a test train were carried out and used for validation of the simulations. The simulations give reasonable results and represent a useful tool for prediction of overturning risk.

Environmental and track perturbations on multiple pantograph interactions with catenaries in high-speed trains

10559
Tue·11:00·3

Jorge Ambrósio† and João Pombo
IDMEC/IST, Portugal†

This work presents a methodology for the analysis of the interaction between catenary and pantographs considering different perturbations. The catenary and pantographs are represented by detailed finite element and multibody models. The pantograph is mounted on a railway vehicle running on a general track including experimentally measured irregularities. The environmental perturbations considered here are the aerodynamics forces resulting from side winds, collected experimentally in a wind tunnel. The contact between the two subsystems is described using a penalty contact formulation. The methodology is applied to the study of the interaction of multiple pantographs with a catenary. It is demonstrated that the influence of the leading pantograph over the quality of contact of the rear pantograph, the consequences of pantograph defects over the contact and the limitation on the running velocities of high-speed trains due to environmental and track conditions

Dynamic characteristics of pseudo-rigid bodies

11264
Tue·11:20·3

Li-Sheng Wang,† Yih-Hsing Pao and Hsin-Min Peng
National Taiwan University, Taiwan†

A pseudo-rigid body is a deformable body with spatial homogeneity of the deformation gradient. While there have been various discussions on the theory and applications, the intrinsic property of the pseudo-rigid body is still in demand. In this paper, the dynamic characteristics of pseudo-rigid bodies are re-investigated on the basis of a variational equation of virtual power for continua. The requirement that the deformation gradient is homogeneous is incorporated as a condition of kinematic constraint in the variational equation, from which the equations of motion are derived. The material property of the deformable body is taken into account through the internal energy and dissipation functions. Based on the variational approach, the internal structure to maintain the pseudo-rigid constraint becomes transparent. In our approach, it is neither necessary to apply the complementary Principle of Balance of Moment of Momentum, nor to adopt the axioms on the kinetic properties.

Analytical and experimental analysis of a parallel leaf spring guidance

11310
Tue·11:40·3

Jacob Meijaard,† Dannis Brouwer and Ben Jonker
University of Twente, Netherlands†

A parallel leaf spring guidance is defined as a benchmark problem for flexible multibody formalisms and codes. The mechanism is loaded by forces and an additional moment or misalignment. Buckling loads, changes in compliance and frequencies, and large-amplitude vibrations are calculated. A previously developed beam element for modelling the leaf springs is shown to be able to describe these phenomena with a limited number of elements. The results are validated by experiments.

Numerical and experimental analysis of an automotive clutch disc

11377
Tue·12:00·3

Samir Sfarni,† Matthieu Malley, Jérôme Fortin and Emmanuel Bellenger
Université de Picardie Jules Verne, France†

We are interested in an automotive clutch disc that allows the progressive coupling and decoupling of motor and transmission during the gear change. It is composed of a thin wavy cushion disc compressed between two friction facings. The disc is the key element of this riveted assembly, because its non linear stiffness allows a progressive axial compression and the gradual transmission of torque. The objective of the present work is to model the load deflection curve and contact pressures of this riveted system. The difficulty to realize a FE Model is due to the complex wavy shape of the disc that generates variable contact areas during the compression phase. The elastic springback occurring after the forming process of the disc and the facings affects the geometry accuracy and alters the FE analysis results. The riveting process induces a complex response of the system, affected by clamping force, clearance, geometry defaults and other phenomena.

Dynamic analysis of rail vehicles and investigation of potential derailment caused by wheelflats

11533
Tue·12:20·3

Wen-Fang Wu,† Sih-Li Chen and Yang-Tsai Fan
National Taiwan University, Taiwan†

A 28-degree-of-freedom model is established to study the dynamic responses of rail vehicles and evaluate the possible derailment caused by wheelflats. Numerical simulation is performed in consideration of the CP341 vehicles to be used in Taipei Rapid Transit Systems. The stability of the vehicle is discussed in detail and compared with available full-scale test data. Both simulation and test results indicate the dynamic stability and derailment quotient of the vehicles meet criteria set by the transit systems authorities.

Development of a dynamic analysis solver using an object-oriented programming method

11019
Thu·14:00·8

Jiwon Yoon,† Sungpil Jung, Taewon Park and Jeongbeom Kim
Ajou University, South Korea†

30 years of research in simulation of multi-body dynamics has brought a great progress in this area. As a result, various dynamic analysis programs have been commercialized. In this paper, the object-oriented technology which is famous for its usefulness in programming technique is introduced to

build the dynamic analysis program. A user can modify and supplement the element in the analysis system, without knowing the details in the analysis system. It is based on several techniques, including inheritance, abstraction, polymorphism, and encapsulation. Then, end users are easily accessible to the customized program because it gives convenient user environment to them. For comparative studies between a customized and a commercial program, simple examples and verification show the reliability and accuracy of the program. This program is also applied to solve the dynamic behavior of humanoid robot for validation of the feasibility of the customized program for further studies.

Dynamics model and algorithm of floating raft with elastic limiters

11170
Thu·14:05·8

Jianming Wen† and Qi Feng
Tongji University, China†

Based on contact dynamics, the multi-degree-freedom dynamic model of floating raft isolation system with elastic limiters is established. The artificial neural network is used to distinguish the contact state of elastic limiters. The example analysis shows that the algorithm of neural network for contact can shorten the time of calcaution. From the example analysis, we get some interesting results that may be useful to actual engineering. When we set the unilateral limiter to the system, we get the best gap corresponding to the displacement of the raft and equipments, respectively. We also notice that the best gap for the raft is not equal to the best gap for the equipments. Setting the bilateral limiter to the system,there is a best gap corresponding to the raft. On the other hand, the maximum displacement of the equipment is increased with the limiter's gap.

Symbolic tools for sensitivity analysis of multibody systems

11235
Thu·14:10·8

Arnaud Sandel,† Philippe Boisse, Lionel Maiffredy and Michel Fayet
National Institute of Applied Sciences, Lyon, France†

Sensitivity analysis consists in quantifying the influence of a design parameter on a performance criterion. The two main analytical methods are here adapted to multibody systems. The direct method, which is based on the simple derivation of the dynamic model, seems to be generally faster than the adjoint-state method, whose advantage lies in calculating the sensitivity of the performance criterion without using the sensitivities of the state variables. However, the adjoint method is here theoretically improved for a non-integral criterion by the introduction of the fundamental solutions; it is also confirmed that this method becomes interesting for an integral criterion on a single time interval and numerous design parameters. The proposed methods are validated on examples like an orthogonal double pendulum or several car models, with the help of Maple and Matlab. Among the future perspectives, it would be interesting to treat closed loops or second-order sensitivities.

Experimental analysis of the A-pillar vortex fluctuations

11632
Thu·14:15·8

Benjamin Levy,† Pierre Brancher and André Giovannini
Institut de Mecanique des Fluides de Toulouse, France†

The A-pillar vortex is a three-dimensional coherent structure that is observed on road vehicles in motion. This coherent structure has a conical shape aligned with the vehicle A-pillar and its dynamics is quite complex. While no vortex breakdown is observed on this vortex, it is nevertheless subjected to oscillatory fluctuations. The objective of the present project is not only to have a better understanding of the flow topology but also to understand what part of it is directly responsible for these fluctuations and whether there is any coherence in its oscillations. This study is performed using Proper Orthogonal Decomposition (POD) method and theoretical analysis on the basis of Particle Image Velocimetry (PIV) campaigns.

Modelling and simulating automobile hysteresis nonlinear dynamical system

11258
Thu·14:20·8

Mingxia Fang† and Qi Feng
Tongji University, China†

For a car including power train, engine cradle, car body, unsprung mass and those substructures with linear and nonlinear joint, the scheme of component mode synthesis is employed to model dynamical systems of the car with hysteresis nonlinearity and rigid-elastic-fluid coupling. For the analysis of non-linear joint substructure about the rubber support, a dynamical experiment was done to achieve the hysteresis mathematical model. Then, the Monte Carlo method is used to simulate the spectrum of random excitation of the road surface and the engine. Based on the motion differential equation of the structure-acoustics coupled system of car, a simulation is carried out in time domain on vibration and interior noise. The numerical results are in good agreement with those from the bench test, which implies that the mathematical model is valid and reliable. This paper also suggests that scheme of component mode synthesis can be extended to model local nonlinear systems with complex structures

On sensitivity methods for vehicle systems under stochastic crosswind-loads

11471
Thu·14:25·8

Christian Wetzel† and Carsten Proppe
University of Karlsruhe, Germany†

Sensitivity analyses are common tools to check the influence of design and excitation parameters on the response of a system. In this paper three stochastic sensitivity methods have been tested and have been compared with respect to the probabilistic crosswind behavior of a characteristic vehicle system. The main focus of this work is on the stability of railway vehicle systems under strong stochastic crosswind-loads as this is a major design criterion. Because of the stochastic wind excitation the crosswind stability is described by the probability of failure that the ground vehicle capsizes.

The multi-impact dynamics in multibody systems

11070
Thu·14:30·8

Caishan Liu,† Bernard Brogliato and Zhen Zhao
Peking University, China†

This paper presents a new scheme for dealing with multi-impact problems, in which the Darboux–Keller's method is used whose the normal impulse is taken as an independent "time-like" variable. A distributing law related to the wave effects of chains of balls appearing in impacts is discovered, and the local energy loss is constrained by an energetic coefficient of restitution. Comparisons between the theoretical predictions and the experimental results found in the literature are presented. Extension of this method into the frictional collisions is carried out and good agreements are also found between the results obtained from simulations and experiments published elsewhere.

Analytical study of the improved seatbelt retractor

11531
Fri·09:15·3

Chanseung Park,† Taewon Park, Sungpil Jung, Kwangyeil Cheong and Yosun Hong
Ajou University, South Korea†

In this paper, an analytical study on the improvement of the performance of a retractor, which is operated when a car accident occurs, is presented. To analyze the retractor system, a dynamic

model is constructed using a commercial multibody dynamic program. To find the characteristic of a clutch's power transmission, an experiment has been done. Dynamic modeling, representing a clutch with spring, is prepared to represent flow of power and belt's retracting. In addition, an experiment on the performance of explosive pressure that affects significantly to the retracting length of a seatbelt has been performed. Amount of belt's retracting is changed according to explosive pressure. And explosive pressure to attain a target retracting length is suggested. By comparing simulation results with experimental results, a reliable dynamic model is created. In experiments and simulations, by redesigning explosive pressure and clutch's effect, performance of retractor is improved and verified.

The dynamic characteristic analysis of the bi-modal tram using the test platform of all wheel steering ECU

11535
Fri·09:35·3

Sooho Lee,† Kijung Kim, Kyungho Moon, Sunghun Choi, Kabjin Jun and Taewon Park
Ajou University, South Korea†

The AWS (All-Wheel-Steering) system is applied to the bi-modal tram to satisfy the required steering performance because the bi-modal tram has extended wheel base and articulated chassis. AWS ECU controls hydraulic actuator according to vehicle driving environment, such as driver steering angle, articulating angle, and vehicle velocity. In this study, the test platform environment is developed for the AWS ECU black box test. The black box test is to analyze input and output signals of the ECU. From the test the algorithm of the ECU can be obtained, even though the information of an ECU is not well known. Using the developed test platform, the control algorithm of the AWS ECU can be evaluated under the virtual driving condition of the bi-modal tram. The control algorithm of the AWS ECU is applied to a multibody dynamics model of the bi-modal tram, and the dynamic characteristic of the bi-modal tram can be analyzed.

Discrete time transfer matrix method for dynamics of multi-rigid-flexible-body system

10999
Fri·09:55·3

Xiaoting Rui,† Bao Rong and Guoping Wang
Nanjing University of Science and technology, China†

By introducing state vectors, developing transfer equations and transfer matrices transfer matrices of flexible bodies and hinges, discrete time transfer matrix method of multibody system used to multi-rigid-body system dynamics developed in recent years is expanded, and discrete time transfer matrix method of multi-rigid-flexible-body system (MRFS-DT-TMM) is developed to study multi-rigid-flexible-body system dynamics. The global dynamics equations are not needed, and the orders of involved matrices are always very small and the computational speed is high irrespective of the size of a multi-rigid-flexible-body system when using this method. The proposed method is simple, straightforward, practical, and provides a powerful tool for multi-rigid-flexible-body system dynamics. The formulations of the method as well as numerical example to validate the method are given.

Coupled simulation of dispersions in multibody systems

10751
Fri·10:15·3

Peter Eberhard† and Florian Fleissner
University of Stuttgart, Germany†

The motion of granular materials and liquids in silo vehicles and tank trucks can have a significant influence on the driving dynamics. Tank geometries and vehicle suspension systems have to be designed carefully to provide stability during breaking and lane change maneuvers. Several approaches for the dynamic simulation of tank vehicles have been proposed in the past decades, mostly based on the coupling of multibody systems and Eulerian fluid simulation methods such as the Finite Volume Method. We present a new approach for the simulation of coupled dispersive particle-fluid systems and multibody systems. The fluid/particle model is thereby based on a meshless Lagrangian approach that provides a much simpler and more robust way of handling free surfaces and moving boundaries. The approach is tested and verified by means of simulations of different steering and breaking maneuvers of tank trucks considering the sloshing load and its interaction with the moving vehicle.

Free vibration of vehicles with interconnected suspensions

11703
Fri·11:00·3

Wade Smith,† Jeku Jeyakumaran and Nong Zhang
University of Technology, Sydney, Australia†

This paper presents a computationally efficient approach for the free vibration analysis of a vehicle fitted with a general, passive hydraulically interconnected suspension (HIS) system. Ideally, interconnected suspensions have the capability, unique among passive systems, to provide stiffness and damping characteristics dependent on the all-wheel suspension mode in operation. A linear half-car model is analysed here as an example to illustrate the application of the proposed methodology. Mathematical details of the derivation of the state space equations which govern the coupled dynamics of the integrated half-car system are described, and a root search scheme for finding the system eigenfrequencies is delineated. The results offer further confirmation that interconnected suspension schemes can provide some control over modal stiffness and damping. The presented approach establishes a scientific basis for investigating the dynamic characteristics of HIS-equipped vehicles.

Motion of an inertially excited two-mass oscillator along a rough plane

11225
Fri·11:20·3

Igor Zeidis,† Klaus Zimmermann, Mikhail Pivovarov and Nikolai Bolotnik
Technische Universitaet Ilmenau, Germany†

A system of two bodies connected by a linear spring is considered. The motion is excited by two unbalance vibration exciters located on the bodies. The rotors of the vibration exciters rotate synchronously in the same direction. The coefficient of dry friction between the bodies and the supporting plane is independent of the direction of the motion. It is shown that for this system of two bodies connected by a linear spring, the direction of motion can be reversed by changing the difference between the natural frequency of the system and the angular velocities of the rotors in sign. The change in the direction of rotation of the rotors is not required. The magnitude of the velocity of the motion can be controlled by changing the phase shift between the rotations of the rotors. An experimental model of the vibration-driven system with unbalance vibration exciters was designed and constructed.

Helix beam finite element based on intrinsic spatial curvatures

10604
Fri·11:40·3

Oleg Dmitrochenko† and Aki Mikkola
Lappeenranta University of Technology, Finland†

A non-linear finite element of a thin beam is proposed for large-deformation and large-rotation dynamical multibody problems. The element employs intrinsic properties of a spatial curve as generalized coordinates: curvature and torsion of the centerline and relative twist of the cross section. This set of 3 degrees of freedom per element is the minimal one and avoids longitudinal elongation of the beam element and associated oscillations in stiff cases. However, it is possible to add the

longitudinal degree of freedom if needed in the applications. Fully non-linear equations of motion are derived for a single element as well as for a mesh of elements. Possibility of applying the articulated body method of linear complexity is considered and compared with conventional numerical methods. Simulation examples and comparison with other known approaches, e.g. with the absolute nodal coordinate formulation, are presented.

Roll-tracking control of an unmanned bicycle using fuzzy logic controller

11437
Fri·12:00·3

Chih-Keng Chen† and Trung-Kien Dao
Dayeh University, Taiwan†

This paper presents a complete procedure of development of dynamic equations and implementation of a roll-tracking control structure of an unmanned bicycle. Firstly, the symbolic equations of motion and constraint equations of a 9-dof bicycle are developed using Lagrange's equations with the help of Maple. The dynamic equations are then employed to implement the bicycle model, which is actually the differential function used by the Runge–Kutta integration method. With the bicycle model, a control structure is designed to control the vehicle so that the roll angle follows a desired input using a fuzzy logic controller. A virtual reality simulation is also implemented to visualize the bicycle dynamics. Results show that the bicycle can track the roll command with short time delay and the control structure can adapt to a wide range of speed.

SM15 :: Nanostructures and MEMS

Chairs: Kyung-Suk Kim (USA) and Francesco de Bona (Italy)

Mon	16:25–17:45	Room 4	Lectures
Thu	14:00–14:55	Hall A	Seminars
Thu	16:00–17:00	Room 10	Lectures

Mechanics and physics of dislocation nucleation in nanostructured metals

11710
Mon·16:25·4

Ting Zhu
Georgia Institute of Technology, USA

Dislocation nucleation is essential to the plastic deformation of nanostructured metals. The free surface and nanostructure interface may act as an effective source of dislocations to initiate and sustain plastic flow. Here, we develop an atomistic modeling framework to address the statistical nature of dislocation nucleation. Such approach enables for the first time atomistic prediction of deformation kinetics at the seconds-to-hours timescale of laboratory experiments. We show interfacial dislocation reactions are the rate-controlling mechanisms in nano-twinned Cu, giving rise to an unusual combination of ultrahigh strength and high ductility. Our results demonstrate a small activation volume associated with surface dislocation nucleation, leading to sensitive temperature and strain-rate dependence of nucleation stress, and providing an upper bound to the size-strength relation in nanopillar compression experiments.

Thermo-elastic size-dependent properties of nano-composites with imperfect interfaces

10666
Mon·16:45·4

Bhushan Karihaloo,[†] Jianxiang Wang and Huiling Duan
Cardiff University, UK[†]

We study the thermo-elastic properties of heterogeneous materials containing nano spherical particles or cylindrical fibres. The interface between the matrix and second phase inhomogeneity is imperfect simulated by an interface stress (ISM) or a linear spring model (LSM) for thermo-elasticity, and a high (HC) or a low conducting (LC) model for conductivities. We relate the effective coefficient of thermal expansion (CTE) to the effective elastic moduli and generalise the Levin formula from macro to nano scale and reveal two relations among the effective elastic moduli generalising the Hill connections to nano scale. In contrast to the perfectly-bonded interfaces, the effective properties of the heterogeneous materials with ISM- and LSM-(or LC and HC) imperfections are dependent on the size of inhomogeneities which is captured by simple scaling laws.

Plectoneme formation in fluctuating DNA

10815
Mon·17:05·4

Prashant Purohit
University of Pennsylvania, USA

The mechanics of DNA super-coiling is a subject of crucial importance to biology, and is being probed by single molecule experimental techniques. An interesting problem within this realm is that of plectoneme formation in DNA as it is simultaneously put under tensile and torsional stress. In this paper we use ideas from the Kirchhoff theory of filaments to find semi-analytical solutions for the average shape of the fluctuating DNA under the assumption that there is no self-contact. Our method consists of combining a helical solution of the rod with a non-planar localizing solution in

such a way that the force, moment, position and slope remain continuous everywhere along the rod. An interesting testable result of our calculations is the prediction of a sudden change in extension at buckling which does not seem to have been emphasized in earlier theoretical models or experiments.

On the ratio between surface tension and the bulk modulus of materials

10828
Mon·17:25·4

Graham Weir
Industrial Research Ltd., New Zealand

Extending mechanics to the nanoscale often leads to the importance of surface energies, and this in turn leads to the interaction between surface tension and elastic parameters. In this paper we will introduce a theory for estimating the non-dimensional ratio of surface tension to the product of the bulk modulus and a lattice parameter, and argue that for many materials this ratio should lie between 0.025 and 0.25, which is demonstrated for some elements around their melting point, for various liquids at room temperature, and for the condensed Noble gases. We also argue that this non-dimensional ratio is related to the fundamental strength of materials.

Estimation of load-capacity of multi-layered porous nanofilters

10140
Thu·14:00·A

Adam Kovacs,† Ulrich Mescheder and Andras Kovacs
Budapest University of Technology and Economics, Hungary†

Porous membranes are often used for nanofiltering purposes in MEMS. Investigated membranes are made from a thin perforated silicon-nitride (SiN) on a porous polysilicon (PS) layer, which is supported and reinforced by single-crystal silicon (c-Si). In order to obtain higher filtration rate the porosity should be as high as possible. The diminishing strength effect can be compensated by the application of c-Si columns as a support grid within the porous layer. In order to estimate the load capacity the elastic material properties of the structure should also be known. Once the material constants had been determined experimentally for SiN- and PS, c-Si reinforcement was replaced by an equivalent third layer. Effective material parameters were then defined as an average of the layers' parameters weighted by the thickness. The mechanical response has been determined numerically using the finite element method. Simulated results are in good accordance with measured values

Anisotropic polling and piezoelectric behaviors in rhombohedral ferroelectric single crystals

10445
Thu·14:05·A

Ai-Kah Soh† and Yicheng Song
The University of Hong Kong, Hong Kong†

Exceptional large piezoelectric coefficients have been experimentally determined in the nonpolar directions of rhombohedral ferroelectric single crystals. In this paper, the anisotropic polling and piezoelectric behaviors in rhombohedral ferroelectric single crystals were studied using the phase field simulation method. Electric and mechanical loading were applied along [001] and [111] directions separately. It was found that polling in [001] direction resulted in reduced hysteresis loop and enhanced longitudinal piezoelectric coefficient. The reduced hysteresis loop should be attributed to different domain switching directions, while the enhanced longitudinal piezoelectric coefficient should be attributed to the large shear piezoelectric coefficient d15. It was also found that PZT with composition near the morphotropic phase boundary (MPB) showed an extraordinarily large increment of longitudinal piezoelectric coefficient due to the increase of dielectric susceptibility near the MPB.

Nanomechanical deflection of DNA chips induced by hybridization exothermic effect

10811
Thu·14:10·A

Neng-Hui Zhang,† Shu-Xiao Wan, Jian-Zhong Chen and Chang-Jun Cheng
Shanghai University, China†

The influence of hybridization exothermic effect on nanomechanical deflections is investigated for DNA chips in label-free biodetections. The time history of exotherm during the linkage of DNA base pairs is described by the free energy of adjacent nucleotides and the related experimental curves. The temperature field is obtained by solving the Fourier's heat conduction equation via the Laplace transformation method. The nanomechanical deflection of DNA chips is predicted by an alternative model for laminated cantilever beams. Numerical results show that the theoretical prediction value of 1.5–2 nm steady-state deflection is within the detectable scope of the optical-beam-deflection readout system.

Characterization of nanoimprinting polymers with laser ultrasonics

11001
Thu·14:15·A

Juerg Bryner,† Timothy Kehoe, Jacqueline Vollmann, Laurent Aebi, Clivia Torres and Jürg Dual
ETH Zurich, Switzerland†

Mechanical properties of polymer thin films used for nanoimprinting are determined using laser acoustic measurements. The contact-free and non-destructive measurement method is explained. The measurements are performed on a short pulse laser pump-probe setup, where bulk wave packets are excited and detected using near infrared laser pulses of less than 100 fs duration. The entire experimental setup is simulated numerically: The heat distribution and thermo-elastic wave excitation in the thin films caused by the laser pulse, the visco-elastic wave propagation, and the photo-acoustic detection. Results of the simulation are shown and an overview of the simulation procedure is given. Measurement series are performed on thin film specimens of two different polymers. The measurements are interpreted with corresponding simulations and compared with profilometry measurements carried out on the same specimens in order to quantify mechanical properties.

Elastic properties of nanostructures with the charged surfaces

11014
Thu·14:20·A

Linli Zhu† and Xiaojing Zheng
Lanzhou University, China†

The nanostructures such as nanowires and nanofilms in nanoelectromechanical systems are easy to be charged when they are working in an applied voltage. It has been revealed that the excess surface charges resulted in the change of the elastic performance of the surfaces for the metal electrode in an electrolyte. Therefore, we discuss the influence of the charged surfaces on the elastic properties of the nanostructures based on the continuum mechanics. Incorporating the excess surface energy from the surface charges into the total surface free energy, the effective elastic modulus is derived by considering the surface energy effect. The theoretical results show that the Young's modulus of the charged nanowire as an example for the nanostructures is dependent notably on the surface charges density and the sign of the surface charges. In addition, the effects of the surface charges on the modulus are associated with the structural geometric dimensions such as the diameter of the wire.

Influence of dislocation distribution density on interface relaxation stress in heteroepitaxial thin films with flexible substrate

11163
Thu·14:25·A

Igor Dobovsek
University of Ljubljana, Slovenia

We consider the problem of relaxation of coherency stresses by lattice misfit dislocations, which can be represented as edge dislocations distributed along the interface, and can be associated with the concept of dislocation density according to the mathematical theory of continuous distributions of dislocations. The orientation of dislocation line is constrained within the plane of epitaxial layer, while the Burgers vector within the same plane is considered as a local variable of the dislocation problem. Under the external stress free conditions the system is then enforced to satisfy the boundary conditions according to the geometry of the epitaxial film and the substrate together with the corresponding compatibility conditions. As a result, the dislocation density tensor can be directly connected with the deformation and rotation tensors and subsequently with the curvature of the system. The closed form solution of the problem is given for the one-dimensional case.

A coarse particle method for nanoimprinting process

11270
Thu·14:30·A

Cheng-Da Wu,[†] Te-Hua Fang and Jen-Fin Lin
Cheng Kung University, Taiwan[†]

A coarse particle method for coupling continuum and molecular models is described. In this method, the continuum model was assumed to be a lattice form and the interaction parameters were provided. The coarse particles can be applied in non-characteristic areas or far away regions from the large deformations to highly promote the efficiency. Defining a critical strain for different lattice sizes is convenient for lattice refinement. In the thermal equilibrium case, the efficiency has exceeded 100 times than that of a classical molecular dynamics (MD) simulation; in addition, great numerical precision is achieved. To test the connection at the molecular/continuum interface, a large deformation case was studied in nanoimprinting process. The results were compared with the MD simulation and it was found that the deviation could be reduced through a moderate adjustment of critical strain on the lattices. This is good evidence that this method is a seamless treatment technology.

Tuning acoustic wave properties by mechanical resonators on a surface

11564
Thu·14:35·A

Maria Dühring,[†] Vincent Laude and Abdelkrim Khelif
Technical University of Denmark, Denmark[†]

Surface acoustic waves (SAW) generated by interdigital transducers (IDT) are extensively used in electromechanical filters and resonators for telecommunication. In this work, the SAW properties are investigated when high aspect ratio (HAR) electrodes are used in the IDTs instead of the conventional thin electrodes. The finite element method is employed to show that the multimodes excited by (HAR) electrodes are combined of a surface wave and vibration in the electrodes. It is found that the confinement of the mechanical energy to the electrodes is higher for increasing aspect ratio which shows that the electrodes act as mechanical resonators and slow down the velocity. It is furthermore found that the group delay of the SAW can be increased up to 20 times when HAR electrodes are used instead of thin electrodes. These results indicate that HAR electrodes can be important in applications as SAW filters, resonators and delay lines in order to make the devices more compact.

Theoretical analysis of three-point bending test of nanowires with surface effects

11591
Thu·14:40·A

Xianwei Zeng,† Weifeng Wang and Jianping Ding
South China University of Technology, China†

The apparent Young's modulus of nanowires has been measured by three-point bending test with the wires deflected by atomic force microscopy tips. Bending test shows that the apparent modulus decreases with increasing wire diameter. To analyze this size-dependent behavior, the deflection of a nanowire with clamped ends subjected to a vertical load at its midpoint is studied using beam theory by including contributions of the bulk and the surface. Analytical solution has been derived for deflection of a nanowire including a parameter which relates axial force due to clamped ends to wire bending rigidity. The parameter can be determined by an algebraic equation. The solution is used to calculate the strain energy of a nanowire including that of the bulk and the surface. By strain energy equivalence, the apparent Young's modulus of a nanowire is expressed as a function of the modulus of bulk material, residual surface stress, surface elastic modulus, and dimensions of a nanowire.

Failure prediction of single-walled carbon nanotubes under uniaxial tension using virial stress theorem

11623
Thu·14:45·A

Tarek Ragab† and Cemal Basaran
State University of New York at Buffalo, USA†

In this paper the stresses in an armchair Single-Walled Carbon NanoTube (SWCNT) under uniaxial loading are calculated using the virial stress theorem till failure. This is compared to other methods used in the literature for calculating the stresses in CNTs. The loading is done under two different strain rates with two different loading procedures and the results are compared. It can be concluded that the method used in the literature for calculating the stresses in CNTs under estimates the strength by around 35%.

On the modelling and decomposition of gradient enhanced electro-mechanically coupled deformation

11790
Thu·14:50·A

Sebastian Skatulla,† Carlo Sansour and Arockiarajan Anrunachalakasi
University of Nottingham, UK†

Electro-active polymers (EAP) fall into the category of so-called smart materials which are characterized by electro-mechanical coupling. Upon electrical loading, EAP exhibit large deformation while sustaining large forces. When it comes to smaller structures, the mechanical response deviates from the prediction of classical mechanics. These scale effects are due to the fact that the size of the microscopic material constituents of such structures can not be considered to be negligibly small anymore compared to the structure's overall dimensions. In this context generalized continua have been proven to account for these kinds of phenomena. Here, a generalized continuum framework is adopted and extended to encompass also electro-mechanical coupling of EAP. The approach introduces new strain and stress measures as well as a modified electric displacement vector which lead to the formulation of a corresponding generalized electro-mechanically coupled variational principle.

Higher-order equations for quantum dot structures in thin solid films

10962
Thu·16:00·10

Peter Evans,[†] Maciek Korzec, Andreas Münch and Barbara Wagner
Humboldt University of Berlin, Germany[†]

The modelling of nanostructures arising in epitaxially grown thin films is important for the study of self-organised quantum dots. Typical models include misfit strain arising from a lattice mismatch with the substrate (driven by the Asaro–Tiller–Grinfeld instability and giving rise to Stranski–Krastanow islands) and/or anisotropy of the free surface energy. Both these types of model give rise to sixth-order partial differential equations with similar structures. One of these is a higher-order variant of the convective Cahn–Hilliard equation, for which we identify new stationary solutions characterised by multiple humps. We use an extension of the method of matched asymptotic expansions that retains exponentially small terms, together with an investigation of the phase space for the corresponding fifth-order dynamical systems, to study these stationary solutions. We extend this model to obtain a more realistic model for quantum dot formation.

Application of molecular statistical thermodynamics to uniaxial tension of ZnO nanorods

11169
Thu·16:20·10

Yilong Bai,[†] Pan Xiao, Fujiu Ke, Jun Wang and Mengfeng Xia
Chinese Academy of Sciences, China[†]

Uniaxial tensile deformation of ZnO nanorods and a phase transformation from wurtzite (WZ) to a body-centered-tetragonal with four-atom rings (BCT-4) structure are examined in terms of both molecular statistical thermodynamics (MST) and molecular dynamics (MD) methods. In fact, MD simulation is very popular, but hardly extended to quasi-static processes in principle, whereas MST method is based on the minimization of Helmholtz free energy in each deformation step to give the most preferable configuration of atoms in the system with higher efficiency in computation than MD method. Both MST and MD simulations show that the phase transformations demonstrate three distinctive stages: (i) an elastic stretch of the WZ structure, (ii) a precipitous drop of stress corresponding to the phase transformation and (iii) the elastic stretch of the BCT-4 structure. Significant size effects on the critical stress for transformation and Young's modulus are observed and analyzed.

Theoretical analysis of adsorption-induced microcantilever bending

11419
Thu·16:40·10

Shou-Wen Yu,[†] Ji-Qiao Zhang, Xi-Qiao Feng and Gang-Feng Wang
Tsinghua University, China[†]

Microcantilever-based techniques can be used to explore the autonomy and property of biomolecules (e.g. DNA and single actin filaments) which, in measurement, are adsorbed on the cantilever surface. An energy method is presented here to predict the cantilever deflection induced by adsorbed atoms/molecules. The cantilever is modeled as a sandwich beam containing two surface layers of a finite thickness and a bulk layer between them. The adsorptions of O atoms on Si(100) and Hg atoms on Au(100) are taken as two representative examples. It can be found that the interatomic interactions play an important role in the mechanical bending of cantilever. We demonstrate that physisorption can induce distinctly different deformation behaviors of cantilevers, which depend not only on the adatoms but also on the substrate material. These results are consistent with relevant experimental observations. This study is helpful for optimized design of microcantilever-based measurement techniques.

SM16 :: Plasticity and viscoplasticity

Chairs: Marc Geers (Netherlands) and Christian Miehe (Germany)

Mon	14:00–16:00	Room 6	Lectures
Mon	16:25–17:45	Room 6	Lectures
Wed	10:40–13:00	Room 5	Lectures
Thu	14:50–15:05	Room 4	Seminars

A finite strain theory of gradient crystal plasticity **11296** Mon·14:00·6

Mitsutoshi Kuroda† and Viggo Tvergaard
Yamagata University, Japan†

A finite strain size-dependent crystal plasticity theory with higher-order gradient effects is presented. The theory does not deviate much from the conventional crystal plasticity theory. Only a back stress effect and additional differential equations for evolution of the geometrically necessary dislocation (GND) densities supplement the conventional theory within a non-work-conjugate framework in which there is no need to introduce higher-order microscopic stresses that would be work-conjugate to slip rate gradients. We discuss its connection to a work-conjugate type of finite deformation gradient crystal plasticity that is based on an assumption of the existence of higher-order stresses. Furthermore, a boundary-value problem for simple shear of a constrained thin strip is studied numerically, and some characteristic features of finite strain are demonstrated through a comparison to a solution for the small strain theory.

A canonical numerical formulation for wrinkling in elastoplastic membranes undergoing large deformations **11102** Mon·14:20·6

Joern Mosler† and Fehmi Cirak
Ruhr University Bochum, Germany†

In this contribution an efficient novel algorithmic formulation for wrinkling at finite strains is presented. In contrast to previous works on numerical membrane approaches, the proposed model accounts for inelastic effects. More precisely, any constitutive model falling into the range of so-called standard dissipative solids (or variational constitutive updates) can be employed. Focus is on finite strain plasticity based on a multiplicative decomposition of the deformation gradient. The key features of the presented formulation is its fully variational structure, i.e., the parameters describing wrinkles or slacks, the plastic deformation and the deformation mapping are computed jointly by minimizing the (relaxed) energy of the respective mechanical system. Hence, standard optimization algorithms can be applied to the numerical implementation. By doing so, a very robust and efficient finite element formulation is developed.

Thermodynamic coarse-graining of dislocation mechanics and the size-dependent continuum plasticity **11266** Mon·14:40·6

Sinisa Mesarovic,† Raghuraman Baskaran, Sreekanth Akarapu and Hussein Zbib
Washington State University, USA†

The error in elastic energy, arising from representing discrete dislocations as continuum distributions, is represented in terms of those same continuum distributions. The resulting theory features boundary/interface energy. All microstructural constitutive relations are derived, and depend only on elastic properties of the crystal and physical lengths. Multiple characteristic lengths, each associated with an active slip system, represent average spacing between discrete slip planes in the system and may evolve with deformation.

Recent progress in the homogenization of elasto-plastic and elasto-viscoplastic inclusion-reinforced composites

11764
Mon·15:00·6

Issam Doghri,† Koen Delaere, Nicolas Bilger, Laurent Adam, Laurent Delannay and Laurence Brassart
Université Catholique de Louvain, Belgium†

We study the micromechanical modeling of elasto-plastic and elasto-viscoplastic materials reinforced with short fibers, particles or more generally inclusions. Due to the unknown interaction between the phases, the prediction of the macroscopic response of heterogeneous materials is a complex task, even in linear elasticity, and the problem becomes much more challenging in the nonlinear regime. Predicting the behaviour of a representative volume element (RVE) of the microstructure submitted to different loads can be done via scale-transition methods. In our work we mainly develop one of them, mean-field homogenization (MFH), which is based on assumed relations between average strain fields in each phase, and represents a very cost-effective predictive tool. But we also conduct direct finite element (FE) analysis of RVEs mainly as an excellent method for verifying and improving MFH predictions.

The effect of void shape on size-dependent void growth

11347
Mon·15:20·6

Christian Niordson† and Viggo Tvergaard
Technical University of Denmark, Denmark†

The effect of void shape on the size-dependent mechanical behavior of micron scale voids in metals is analyzed. Axisymmetric cell models, representing a three dimensional distribution of both prolate and oblate voids, are analyzed numerically using a finite strain generalization of the strain gradient plasticity theory by Fleck and Hutchinson (2001). It is shown that the size effects during growth for both prolate and oblate voids is roughly on the same order of magnitude as for spherical voids. On the other hand, important differences are found in the coalescence behavior. The results presented in this study will provide a detailed analysis of the effect of void shape on the size-effects in void growth and coalescence.

Characterization of strain rate dependent deformation behavior of carbon-black filled rubber

10160
Mon·15:40·6

Yoshihiro Tomita,† Masaki Kondou and Masato Naito
Graduate School of Engineering, Japan†

The strain rate dependent deformation behaviors of rubber containing Carbon-Black (CB) fillers are investigated by computational simulation with the homogenization method and a constitutive equation for rubber derived by employing a nonaffine molecular chain network model for an elastic deformation and the reptation theory for a viscoelastic deformation. The results clarified the essential physical enhancement mechanisms of deformation resistance and hysteresis loss for rubber filled with CB with different distribution patterns under different rate of deformation. An aggregated distribution of CB suggested the presence of nondeforming region which enhances the resistance to deformation and hysteresis loss. The strain rate dependence of rubber intensifies the hysteresis loss which markedly depends on the strain rate applied in the complex way. Finally, we explore the realistic deformation behavior of CB-filled rubber by employing 3D-transmission electron microscope image of CB morphology.

Incremental variational principles with application to the homogenization of nonlinear dissipative composites

10279
Mon·16:25·6

Pierre Suquet† and Noel Lahellec
Centre National de la Recherche Scientifique, France†

This study aims at predicting the effective behaviour of composite materials under loading conditions where reversible and irreversible effects are coupled (e.g. metal matrix composites under cyclic loading at high temperature). The constitutive relations for the individual constituents derive from two potentials, a free-energy function which encompasses all the energy available in the system at equilibrium, and a dissipation potential which describes the evolution in time of irreversible processes. After time-discretization, the evolution equations are reduced to the minimization of an incremental energy function. This minimization problem is rigorously equivalent to a nonlinear thermoelastic problem with a nonuniform transformation field. Then, approximations are introduced by approximating nonuniform eigenstrains by piecewise uniform eigenstrains and by linearizing the nonlinear thermoelastic problem. Applications to elasto-viscoplastic phases under cyclic loading will be given.

On the link between discretization and higher order homogenization of elastic-plastic composites

10596
Mon·16:45·6

Kenneth Runesson† and Fredrik Larsson
Chalmers University of Technology, Sweden†

A variational framework is proposed within which the order of homogenization on Quadrature Subscale Volume Elements will be determined by the polynomial order of the macro-scale element approximation (and is not determined a priori). This feature is part of a novel adaptive algorithm bridging the two extremes of complete scale separation with coupled macro-subscale resolution and complete scale mixing with only single-scale resolution. As a consequence, the actual order of homogenization is problem-dependent and (ii) the need for "higher order continuum models" on the macro-scale is completely avoided since the homogenization variables "live in the discrete world". Numerical results will be presented for an elastic-plastic composite subject to different degree of scale separation and different order of approximation. In particular, the sensitivity of the results with respect to the degree of scale-mixing will be discussed.

Mesoscopic modeling of the relaxation of intrinsic stress in thin films by grain boundary diffusion and plasticity: a discrete dislocation dynamics approach

10556
Mon·17:05·6

Erik van der Giessen† and Can Ayas
University of Groningen, Netherlands†

When thin films deposited on substrates are cooled down from the deposition temperature, high stresses tend to develop as a consequence of the mismatch in thermal expansion and as a result of the deposition process. These stresses may relax by diffusion of ad-atoms into grain boundaries, but also by dislocation plasticity. We present a methodology to simulate both relaxation mechanisms within a unified two-dimensional framework based on discrete dislocation dynamics. Dislocation plasticity is described by the nucleation and motion of dislocations on multiple glide systems inside crystallites, taking into account the long-range interaction between dislocations as well as their image fields. Grain boundary diffusion is incorporated into this approach by formulating mass transport along grain boundaries in terms of the "climb" of discrete grain boundary dislocations.

Simulation of deformation and fracture of metal/ceramic interfaces

11683
Mon·17:25·6

Siegfried Schmauder† and Amir Siddiq
University of Stuttgart, Germany†

The deformation behaviour of niobium single crystals has been simulated using crystal plasticity theory. Effects of different niobium single crystalline material orientations on crack initiation energies of the bicrystal niobium/sapphire four-point-bending-test specimens are presented for a stationary crack tip. The trends of crack initiation energies are found to be similar to those observed during experiments. Crack propagation analyses of niobium/alumina bicrystal interface fracture have been performed using a cohesive modelling approach for three different orientations of single crystalline niobium. The results show that cohesive strength has a stronger effect on the macroscopic fracture energy as compared to work of adhesion. A correlation among the macroscopic fracture energy, cohesive strength, work of adhesion and yield stress of niobium single crystalline material will be derived.

Computational challenges in finite plasticity from a mathematical view point

11958
Wed·10:40·5

Carsten Carstensen† and Robert Huth
Humboldt University, Germany†

The numerical simulation of an elastoplastic evolution problem encounters severe difficulty in at least three aspects: (i) enforced microstructures and mesh-dependent computational results arise in a typical time step of the nonconvex minimisation problem. (ii) the incremental models for the time-evolving effective problem are possibly well defined in each time-step while the convergence of the implicit time-discretisation may be uncertain (iii) the effective model is described by some unknown quasiconvex envelope of a given energy density which has to be computed in a numerical relaxation step.

Grain size effect and intrinsic material length of a polycrystal

10047
Wed·11:00·5

Ke-Shi Zhang
Guangxi University, China

The intrinsic material length and Hall–Petch relationship of polycrystals are investigated through crystal plasticity analysis. A strain gradient function that takes intrinsic material length as its parameter is introduced, and it is applied to describe the subjoined obstacle to crystal slip initiation and slip progress caused by high strain gradient. This function is introduced in a strain gradient crystal plasticity model. A Voronoi multi crystals aggregate that is adopted as a RVE (representative volume element), and it is combined with the strain gradient crystal plasticity calculation to emulate the mechanical behavior of a polycrystalline material. Then the grain size effect (Hall-Petch relationship) with the intrinsic material length is investigated, and further the method to determine the value of intrinsic material length is proposed.

Hardening and softening in micro and nanoplasticity

11497
Wed·11:20·5

Carl Dahlberg† and Peter Gudmundson
Royal Institute of Technology, Sweden†

Modeling of a boundary sliding phenomena, active at really diminished length scales, shows promising qualitative results in predicting the inverse Hall–Petch effect. Both strain gradient plasticity and boundary sliding are considered on a model of a laminate structure. For a very small laminae

thickness, corresponding to a very small grain size, sliding is the dominating mechanism and the strength then decreases with decreasing thickness. For larger thicknesses, strain gradient plasticity is controlling the deformation and the strength is instead increasing with decreasing thickness. Hence, the competition between two deformation mechanisms can qualitatively capture the observed yield behaviour in metallic materials.

Discrete and continuum dislocations and plastic hardening of crystals

10886
Wed·11:40·5

Pilar Ariza,† Ashwin Ramasubramaniam and Michael Ortiz
Universidad de Sevilla, Spain†

We present a discrete mechanics model for dislocation based plasticity in BCC metals. Dislocations are treated within this theory as energy minimizing structures that lead to locally lattice-invariant but globally incompatible eigendeformations. Simulations with our model are shown to naturally produce strain-hardening, irreversibility and hysteresis, mediated by dislocation interactions.

Ductile damage development in friction stir welded aluminum joints

10776
Wed·12:00·5

Kim Nielsen
Technical University of Denmark, Denmark

Ductile damage development in a Friction Stir Welded aluminum joint subjected to tension transverse to the weldline is analyzed numerically by FE-analysis, based on a total Lagrangian formulation. An elastic-viscoplastic constitutive relation is applied accounting for nucleation and growth of microvoids to coalescence. Main focus in the paper is on the interaction between changes in the yield stresses in different regions of the weld, the damage development and the position of the final failure. It is shown that ductile damage development in a FS-welded tensile specimen is well described by the GTN-model. Furthermore, the variation of the yield stress profile transverse to the weldline is shown to have a significant influence on the damage development. A shift in the mode of final failure from a shear band-like failure in the softest thermo-mechanically affected zone to a neck governed failure in the harder nugget zone is observed.

Bauschinger effect in freestanding thin films modeled by discrete dislocation plasticity

11189
Wed·12:20·5

Lucia Nicola,† Ranjeet Kumar and Erik van der Giessen
Delft University of Technology, Netherlands†

Experiments by Rajagopalan *et al.* (Plastic deformation recovery in freestanding nanocrystalline aluminum and gold thin films. Science 315:1831-1834, 2007) show that early reversed plasticity takes place upon unloading of strained thin films. The films tested are freestanding unpassivated aluminum and gold films, 200 nm thick, with a few grains across the film thickness. Discrete dislocation plasticity simulations appear to be capable of predicting a Bauschinger effect in unpassivated films with more than one grain across the film thickness. Results of the simulations will be analyzed to establish if early reversed plasticity is caused by (1) back-stress related to dislocations piled up at grain boundaries during loading or (2) elastic energy stored in small dislocation-free grains.

Viscoplasticity of ice single crystals loaded in torsion: experiments and discrete dislocation dynamics simulations

11181
Wed·12:40·5

Marc Fivel,† Juliette Chevy and Paul Duval
SIMaP-GPM2, France†

Viscoplastic behaviour of ice single crystals is strongly anisotropic since plasticity essentially propagates by glide of dislocations in basal planes. In this paper, creep torsion tests are carried out on cylindrical ice single crystals machined so that the torsion axis matches with the crystallographic c axis. This induces shear stresses in the basal systems pushing basal screw dislocations toward the symmetry axis and no macroscopical force can drive the dislocations along any non-basal direction. Therefore, when confined to basal systems, dislocation glide can never explain the plastic flow experimentally observed. In this presentation we propose to invoke dislocation multiplication through cross-slip on prismatic systems to justify ice viscoplasticity. The scenario is tested using discrete dislocation dynamics simulations and comparisons with X-Rays analysis are performed.

Influence of die rotating speed on forward extrusion

11641
Thu·14:50·4

Xiang Ma† and Matthew Barnett
SINTEF Materials and Chemistry, Norway†

There is an increasing interest in employing severe plastic deformation processes to promote the formation of ultra-fine grain structures in metals. One of these involves extrusion under imposed die rotation. A certain amount of twist shear strain, which assists in refining microstructures, can be imposed into the bulk of materials. However, not all the power from the rotating tool can be transferred into shearing the workpiece, and this creates a circumferential slippage between the tool and the material. A cyclically rotating die has been used to get a better control of microstructural refinement with a strain path change. The circumferential slippage must be taken into account in assessing twist shear. In this work an upper bound analysis is carried out to evaluate the slippage parameter and the decreased extrusion pressure. A satisfactory agreement is obtained between tests and predictions.

An influence of torsional cycles on the uni-axial tension of selected materials

12118
Thu·14:55·4

Zbigniew Kowalewski† and Tadeusz Szymczak
Motor Transport Institute, Poland†

This paper presents experimental results of investigations carried out on engineering materials subjected to monotonic tension with simultaneous cyclic loading due to torsion. Three different materials were tested, i.e. 2024 aluminium alloy used in aircraft industry, pure copper, and P91 steel commonly used in power plants. An influence of strain amplitude, frequency and shape of cyclic loading signal on the tension characteristics under monotonic loading is studied. The results show that cyclic torsion has a significant influence on the tension parameters variations. It is expressed by an essential decrease such mechanical parameters as the proportional limit and conventional yield point. Depending on the material the difference between values of these parameters for tension and tension with torsion fluctuates from more than two times in the case of 2024 aluminium alloy to more than eight times for copper.

The relationship between deformation-induced texture

10355
Thu·15:00·4

Long Shiguo,[†] Ma Zengsheng, Pan Yong and Zhou Yichun
Xiangtan University, China[†]

The relationship of deformation texture and mechanics of nickel coatings under tension was studied by XRD and nano-indentation. It is found that after deformation, there is no new texture appear for nickel coatings but the change of the intensity of the deformation textures, especially the Ni (111) decreasing largely. The investigation for the nano-indentation shows that the indentation depths increase with the increasing tensile strain under the same load. Hence, the hardness and elastic modulus both decrease. With decreasing intensity of Ni (111) texture an increasing displacement and a decreasing hardness and elastic for nickel coatings were found. The creep values of nickel coatings increase with the increasing at the same peak indentation force.

SM17 :: Stability of structures

Chairs: Henrik Jensen (Denmark) and Nick Triantafyllidis (USA)

Thu	09:15–10:35	Hall D	Lectures
Thu	14:00–14:45	Room 2	Seminars
Thu	16:00–17:00	Room 6	Lectures

Structural and failure performance of load-carrying lattice structures

10996
Thu·09:15·D

Hans Obrecht,† Ulf Reinicke and Marcel Walkowiak
Technische Universität Dortmund, Germany†

Two-dimensional structures having suitably designed macroscopic lattice topologies may exhibit significantly more favorable thermo-structural characteristics than conventional monocoque plates and shells of the same shape, dimensions and weight. The presentation will explore the extent to which lattice topologies and material combinations may influence the mechanical properties, load-carrying and failure behavior of weight-efficient structural components subjected to quasi-static, thermal and impact loads.

Buckling of single-crystal silicon nanolines under indentation

11162
Thu·09:35·D

Rui Huang,† Bin Li, Min Kang and Paul Ho
University of Texas at Austin, USA†

Atomic force microscope (AFM) based indentation tests were performed to examine mechanical properties of parallel single-crystal silicon nanolines (SiNL), fabricated by a process combining electron-beam lithography and anisotropic wet etching. The SiNLs have straight and nearly atomically flat sidewalls, and the cross section is almost perfectly rectangular with uniform width and height along the longitudinal direction. The measured load-displacement curves from the indentation tests show an instability with large displacement bursts at a critical load ranging from 480 μN to 700 μN. This phenomenon is attributed to a transition of the buckling mode of the SiNLs under indentation. Using a set of finite element models, we analyze the indentation-induced buckling modes and investigate the effects of tip location, contact friction, and substrate deformation on the critical load of mode transition.

Mechanically-triggered transformations of pattern and phononic band gaps in periodic elastomeric structures

11399
Thu·09:55·D

Katia Bertoldi† and Mary Boyce
Massachusetts Institute of Technology, US Minor Outlying Islands†

Periodic elastomeric structures are subjected to uniaxial compression and novel transformations of the patterned structures are found upon reaching a critical value of applied load. Bloch wave analyses conducted within a finite element framework clearly show the mechanism of the pattern switch to be a form of microstructural elastic instability, giving reversible and repeatable transformation events as confirmed by experiments. This behaviour provides opportunities for transformative phononic crystals which can switch in a sudden, but controlled manner. The transformations are found to strongly affect the in-plane phononic band gaps, resulting in the closure of existing band gaps and in the opening of new ones. Band gaps and their transformations can be tuned to frequency domains of interest by varying the geometry as well as material. The pattern transformation phenomena can be utilized in photonic applications using appropriate materials and pattern length-scales.

Lüders bands induced localization and propagation of curvature in steel tubes under pure bending

10980
Thu·10:15·D

Stelios Kyriakides,† Ali Ok and Edmundo Corona
University of Texas at Austin, USA†

Lüders bands is a material instability manifested as localized deformation. A combination of experiments and analysis was used to examine the effect of Lüders bands on bending of steel tubes. Tubes with D/t of 18.8 were bent in a four-point bending setup under end-rotation control. Following the elastic regime the moment traced a somewhat ragged plateau during which inclined bands appeared on the top and bottom surfaces and the curvature localized. The higher curvature zones then spread along the tube at a nearly constant moment. When the whole tube was thus deformed, the moment gradually increased with uniform curvature and eventually failed by localized diffuse ovalization. The two-curvature regime was reproduced numerically using a stress-strain response with an up-down-up branch followed by hardening. The analysis reproduced the experimental events including the initiation of the Lüders deformation, the moment plateau, its extent, and the curvature localization and propagation.

Thermal post-buckling behavior of FG panels in supersonic airflows

10038
Thu·14:00·2

Ji-Hwan Kim† and Ki-Ju Sohn
Seoul National University, South Korea†

Functionally graded materials(FGMs) are used in high temperature environments, and typical form of FGMs composed of ceramic and metal have been developed as high-heat-resistant materials. In particular, FG panels made of ceramic and metal are used for skins of spacecrafts which are exposed to extremely high temperatures during the re-entry status. Therefore, post-buckling characteristics of FG panels subjected to combined aerodynamic and thermal loads can be an important issue. In this study, material properties of the FG panels are assumed to be continuously varied in the thickness direction according to a simple power law distribution. Further, temperature independent material properties are assumed, and both uniform and gradient temperature elevations throughout the panel thickness are considered to simulate a temperature rise due to the aerodynamic heating.

Multi-bifurcation analysis for the multi-folding structures

10460
Thu·14:05·2

Ichiro Ario† and Andrew Watson
Hiroshima University, Japan†

This paper reviews the theoretical basis for the dynamic numerical analysis to examine the elastic stability of a folding multi-layered truss. The analysis allows for geometrical non-linearity and contact between nodes and is based upon bifurcation theory. Comparisons are made between experimental folding patterns and the patterns obtained from the numerical method in which bifurcations are demonstrated as elastic unstable snap-through behaviour. Several folding patterns are identified during the elastic instability where the folding behaviour of the truss is a function of the initial geometry and velocity of the dynamic loading. The authors suggest that the understanding of the behaviour will be very useful for the development of light weight structures subject to bifurcation.

Wrinkling of thin rectangular plates under longitudinal tension **10758** Thu·14:10·2

Barrie Fraser† and Charlie Macaskill
University of Sydney, Australia†

The wrinkling of flat rectangular sheets subject to in-plane stress fields due to a variety of edge loadings or displacements. These problems are of considerable industrial interest where thin sheet material is being transported between rollers under tension. Many authors, use energy methods to solve these problems. The energy methods are equivalent to finding approximate solutions to the von Kármán equations for the transverse deflections of a thin elastic plate. The solutions are approximate because the functional form of the in-plane stress field and the out of plane displacement functions that are assumed are only approximate. The problem is to specify simple functions that satisfy all of the boundary conditions. This is the case for the stress-free lateral edge boundary conditions of this problem. I shall discuss a solution to the title problem obtained by direct numerical solution of the von Kármán equations.

The computation of sensitivity analysis of stability problems of steel plane frames **10865** Thu·14:15·2

Zdenek Kala,† Abayomi Omishore and Libor Puklicky
Brno University of Technology, Czech Republic†

The article deals with the analysis of the influence of initial imperfection on load-carrying capacity of a steel frame with columns under axial compression. Initial imperfections are defined by their statistic characteristics, obtained from experimental research. The influence of the initial imperfection on the observed output is quantified with the use of so called stochastic sensitivity analysis based on Sobol's Order Sensitivity Indices and nonlinear FEM. Real experiments are simulated on computers. Results can be used for the specification of those input variables, which should be in production checked with increased accuracy. For dominant variables it is possible to aim at decreasing their variability, which is inevitably given by production inaccuracy. The main purpose of the presented paper is to give basis usable to increasing the reliability of designed constructions.

A new result in linear stability **11012** Thu·14:20·2

Jean Lerbert
The University of Evry-Val-d'Essonne, France

In this work, we show a remarkable property of linear nonconservative undamped systems. Using a new criterion of static stability that differs from divergence but coincides with for conservative systems, we prove a partial implication of linear stability. More precisely, if $P(x) = \det(Mx + K)$ is the characteristic polynomial of the system, it is known that the linear stability is ensured by two conditions: the coefficients of P must be positive (1) and the discriminant (defined through the resultant of P and P') must be positive too (2). We prove here that, for any matrix K, symmetric or not, the first condition holds if and only if K is positive definite (i.e. for all $X \neq 0$ in $\mathbf{R}^n$, ${}^tXKX > 0$) which is the new criterion of static stability.

Plastic buckling and post-buckling of rectangular plates, experiments and their simulation by FE computations

11037
Thu·14:25·2

Suresh Shrivastava,† Kamal Berrada and Bing Liu
McGill University, Canada†

To resolve the so-called Plastic Buckling Paradox, compression tests were performed on square Al tubes. The tests mimic the buckling of long simply supported rectangular plates in axial compression. Initial out-of-plane imperfections of the tube sides were measured and their growth recorded. The buckling occurred in the strain-hardening range. The recorded max stresses were compared with the bifurcation stresses from the two common plasticity theories. The well-accepted J2 incremental theory gave unrealistically high stresses. But, unexpectedly, the stresses from the J2 deformation theory were significantly lower. Thus, neither set of the bifurcation stresses was accurate. Buckling was then approached as an imperfection growth problem. Nonlinear FE analyses were conducted using the specimen data and initial imperfections. The incremental theory now provided the max stresses much closer to the experimental ones, thus confirming its validity and imperfection sensitivity experimentally.

A beam element for stability analysis of thin-walled frames with flexible connections

11103
Thu·14:30·2

Goran Turkalj† and Ivo Alfirevic
University of Rijeka, Croatia (Hrvatska†

This paper presents a two-nodded beam-type finite element for the numerical simulation of stability behavior of flexibly connected space frames composed of the straight and prismatic thin-walled beam members. Equilibrium equations of a 14-dof beam element are derived by applying linearized virtual work principle and introducing the nonlinear displacement field of asymmetric thin-walled cross-sections, which accounts for restrained warping. Material is assumed to be homogeneous, isotropic and linear, while internal moments are calculated by engineering theories: Euler–Bernoulli theory for bending and Vlasov theory for torsion. Flexible connections are allowed to occur at element nodes by modifying elastic and geometric stiffness matrices of a conventional beam element and for this a special transformation matrix is derived. Stability analysis is performed in an eigenvalue manner, while connection characteristics are represented by their initial stiffness.

Analysis on aeroelastic dynamics of a rotating laminated disk with viscoelastic core layer

11367
Thu·14:35·2

Xingzhe Wang† and Longfei Li
Lanzhou University, China†

Rotating disks as the basic elements are widely utilized in various machines like floppy disks, hard disks, turbines, gyroscopes and annular saw-blades. In the present paper, a dynamic model is proposed for a laminated disk with viscoelastic core layer rotating in air. The all fundamental equations and boundary conditions of the rotating laminated disk are derived based on Hamilton's principle. The aeroelastic dynamic characteristics of traveling waves for the rotating laminated disk are analyzed by Galerkin's Method where the frequency-dependent complex modulus model is adopted for the viscoelastic layer. The effects of geometrical and material parameters on frequencies and damping of traveling waves for the rotating laminated disk, as well as the dynamic stability are discussed. The results show that the critical and flutter speeds related to the rotating laminated disk stability can be improved by choosing proper geometrical and material parameters of the viscoelastic layer.

Local lattice instability analysis on amorphous metals: effect of free surface

11686
Thu·14:40·2

Masaomi Nishimura,† Yoshihiro Tomita and Kisaragi Yashiro
Kobe University, Japan†

In order to eliminate the complexity of periodicity and to discuss the surface effect, the amorphous prism and sheet of pure Ni are subjected to tension by means of the molecular dynamics simulation. Then we have discussed the local stability, or the positiveness of atomic elastic stiffness coefficients. At the initial equilibrium, just the surface region of 0.5 nm thick has the higher ratio of unstable atoms than the interior region. The unstable atom ratio transiently decreases by the tension for both prism and sheet; and we have concluded that this relaxation takes place only in the region of 2 nm from the surfaces. Contrary to the bulk amorphous, the unstable atoms show much higher tensile stress than the stable ones; however, if we eliminate the surface atoms from evaluation, the tendency of the atomic stress on stable and unstable atoms is almost same as the bulk amorphous. Thus the tensile stress of the unstable atoms on surfaces shifts the stress the stress-strain curves.

Stress focusing in twisted thin elastic plates

11508
Thu·16:00·6

Ciprian Coman† and Andrew Bassom
University of Glasgow, UK†

The work presented here reconsiders the classical stability problem for the deformation experienced by a stretched thin elastic strip when its ends are subjected to small twisting moments. Our main interest is in the limit $h/b \to 0$, where $2h$ and b are the thickness and, respectively, the width of the plate. Singular perturbation methods allow to show that the critical buckling eigenmodes display localised behaviour. In the axial direction the deformation pattern is characterised by a number of regular ripples running between the two short edges of the elastic strip, whilst the transverse deformation is concentrated along the longitudinal symmetry axis and decays exponentially near the long edges. Numerical results that corroborate the excellent accuracy achieved by the asymptotic formulae are included as well.

Large deformation and instability in hydrogels

11644
Thu·16:20·6

Zhigang Suo,† Xuanhe Zhao and Wei Hong
Harvard University, USA†

Hydrogels have enormous potential for making adaptive structures in response to diverse stimuli. This paper formulates a nonlinear field theory of hydrogels. The free energy of the gel results from two molecular processes: stretching the network, and mixing the network with the water molecules. The theory is illustrated with a structure demonstrated recently, in which nanoscale rods of silicon were embedded vertically in a swollen hydrogel, and the rods tilted by a large angle in response to a drying environment (Sidorenko *et al.*, Science 315, 487, 2007). Here we show that this behavior corresponds to a bifurcation at a critical humidity. Above the critical humidity, the rods stand vertical, enabling the hydrogel to develop tension and retain water. Below the critical humidity, the rods tilt, enabling the hydrogel to reduce thickness and release water. We further show that the critical humidity can be tuned.

The initiation of strain nonuniformity in thin-walled cylinders subjected to cyclic torsion analogous to internal buckling

11691
Thu·16:40·6

Masami Kobayashi[†] and Koji Uetani
The University of Shiga Prefecture, Japan[†]

The occurrence of nonuniform strain has been observed in an experimental study concerning steel circular tubes subjected to cyclic torsion. This nonuniformity is supposed to be caused by the similar phenomenon to internal buckling of a rigidly confined continuum shown by Biot and is expected to be predicted by applying symmetry limit theory, established by the authors for predicting branching phenomena under cyclic loading. The purpose of this study is to develop a new theory for predicting the initiation of strain nonuniformity in cylinders subjected to cyclic torsion. From the bifurcation analysis of a steady-state path, defined as a continuous sequence of steady states, the deformation mode with very short wavelength is obtained, analogous to internal buckling. Also it is shown that this short-wave mode under cyclic torsion is different from that of the internal buckling under monotonic torsion and that the former appears at much smaller amplitude than the latter.

SM18 :: Structural optimization

Chairs: Mike Xie (Australia) and Byung Kwak (South Korea)

Mon	16:25–17:45	Room 5	Lectures
Thu	14:30–14:40	Hall C	Seminars
Fri	09:15–10:35	Hall E	Lectures
Fri	11:00–12:20	Room 4	Lectures

Topological design of isotropic composites

10326
Mon·16:25·5

Vivien Challis,[†] Anthony Roberts and Andy Wilkins
University of Queensland, Australia[†]

We use the level-set method to find two-phase isotropic composite microstructures which are optimized for bulk modulus and conductivity. One phase is stiff and insulating whereas the other is conductive and mechanically compliant. Composites with the Schwartz primitive and diamond minimal surfaces as the phase interface are numerically optimal for bulk modulus and conductivity. Since these composites are not isotropic their stiffness under uniaxial loading varies with the direction of the load. We present three microstructures which have similar conductivity and are at least 16% stiffer under uniaxial loading than the Schwartz composites when loaded uniaxially along their weakest direction. Cross-property bounds can show the near-optimality of our optimized microstructures. Our results prove the capabilities of the level-set method for microstructure design.

Efficient optimization-based form finding of cable nets in uniform fluid flow

11049
Mon·16:45·5

Michael Winther,[†] Niels Olhoff and Kurt Hansen
Aalborg University, Denmark[†]

We present a very efficient optimization-based method of determining the deformed configuration of large scale, linearly elastic pelagic (mid-water) or bottom trawls, when subjected to hydrodynamic forces, and bottom contact conditions during fishing. Based on analytical expressions of the internal elastic energy of the netting, and the potential energy of the external hydrodynamic forces, we determine the equilibrium configuration of the trawl by minimizing its total potential energy with respect to the positions of the knots, taking the bottom contact constraints into account. As the hydrodynamic forces are non-conservative and depend on the configuration of the trawl, we have constructed a nested procedure of successive iterations, where the positions of the knots are determined in an inner loop of iterations subject to fixed values and orientations of the external forces, and these forces are updated for each new sequence of iterations in the inner loop of the numerical procedure.

Topology optimisation for micropolar elastic solids

11095
Mon·17:05·5

Yutaka Arimitsu,[†] Zhiqiang Wu, Hiroto Kawano and Yuji Sogabe
Ehime University, Japan[†]

The authors developed the finite element method (FEM) for micropolar elastic solids and applied it to the problem of topology optimisation. The weighted residual method and four-node isoparameteric elements were employed for the FEM analysis. The solid isotropic material with penalization (SIMP) method and the gravity control function were employed in the optimisation procedure. To test the numerical solutions, the bending problem of the cantilever was used. In this analysis, complicated structures such as bone tissues appear when the coupling number increases. Since the checkerboard structures are more apt to appear in the optimisation process for micropolar solids than in classical elasticity, filtering (the gravity control function employed in this paper) or other techniques are required to obtain practical solutions. The proposed method could potentially solve the optimisation problems of biomaterials.

On optimization of involute gear teeth

11155
Mon·17:25·5

Niels Pedersen
Technical University of Denmark, Denmark

For the design of gears the stress due to bending plays a significant role. The stress from bending is largest in the root of the gear teeth, and the magnitude of the maximum stress is controlled by the nominal bending stress and stress concentration due to the geometric shape of the tooth. In this work the bending stress of involute teeth is minimized by shape optimizing the tip of the cutting tool. By redesign of the tip of the cutting tool we achieve that the functional part of the teeth stays the same while at the same time the root shape is changed so that an improvement in the stresses results. The tool tip shape is described by a parameterization that use the super ellipse as the central shape. The shape of the cut tooth that is the envelope of the cutting tool is found analytically. The parameterization includes the standard ISO tooth. Practical simple changes in the design of the tool tip is shown to result in large improvements of the bending stresses.

Topology optimization of continuum by successive approximation

10214
Thu·14:30·C

Sei-ichiro Sakata[†] and Fumihiro Ashida
Electronic Control Systems Engineering, Japan[†]

This paper describes a new approach for approximate topology optimization. Since the topology optimization problem generally has a large numbers of design variables, a successive approximate optimization method is proposed. Constructing a surrogate for an entire solution space with a large numbers of design variables will be difficult, while in the proposed method, the approximation process is divided to two sub-approximation processes as linear (local) and non-linear (non-local) approximation. The linear approximation is constructed at a current location in a solution space, and the non-linear approximation is constructed for a current optimizing direction. The key idea is the use of the perturbation method for constructing the linear approximation. The proposed method is applied to a two-dimensional topology optimization problem. A reasonable result can be obtained and a computational cost for each optimization step can be reduced to about 10-15% of the conventional method.

The optimum design of a rack and pinion gear using the Taguchi method

11440
Thu·14:35·C

Sungpil Jung,[†] Sungmoon Park, Chanseung Park, Taewon Park and Taeckrim Song
Ajou University, South Korea[†]

In this study, the geometry of a rack and pinion gear is optimized using the Taguchi method. The design program for a rack and pinion gear is developed using MATLAB. 3D dynamic model of a seatbelt retractor is created to estimate the performance of the rack and pinion gear. The simulation result and experiment data for retracting length and tension of a seatbelt are compared and the reliability of the model is verified. Increasing the retracting length is set as an objective function and the number of teeth, module, pressure angle and the tip radius of a tool are set as

design variables. For efficient experiments, a $4 \times 2 \times 2$ orthogonal array is created and the SN ratio is calculated using results of various dynamic simulations. On the basis of the optimal design result, the rack and pinion gear is redesigned, and after applying it to the dynamic model its performance is predicted. The actual experiment for the optimized rack and pinion gear is processed and the optimal design result is verified.

11825
Fri·09:15·E

Error estimate based remeshing strategy for shape optimization using radial basis functions

Daniel Wilke,† Albert Groenwold and Schalk Kok
University of Pretoria, South Africa†

We present an error estimate based remeshing strategy for shape optimization where we use the error field of a current design to generate the mesh for the next design. Due to remeshing the number of nodes, elements and element connectivity changes between consecutive designs which becomes problematic when mapping the error field between designs. This mapping problem is circumvented by using radial basis functions to map between consecutive designs. The resulting remeshing strategy also allows for the computation of analytical sensitivities. The changes in number of nodes and elements also introduces discontinuities into the cost function and constraints of the shape problem. We are able to successfully optimize the resulting discontinuous shape problems by employing gradient-only optimization.

12088
Fri·09:35·E

Optimum material design of maximum structural seepage under compliance constraint

Gengdong Cheng† and Shengli Xu
Dalian University of Technology, China†

This paper studies optimum design of structure made of homogeneous anisotropic materials with periodic microstructure. Structural size, shape and topology are given. Part of structure is subject to external forces. One surface of structure immerses in fluid and fluid under pressure seeps out at another surface. The optimization aims at maximum structural seepage constrained on static compliance performance and material porosity, with material microstructural topology being design variables. Structural topology optimization approach is applied to establish the two-scale problem mathematical formulation. In micro scale, effective material properties are calculated by the homogenization approach. In macro scale, static compliance and seepage performance is solved by the corresponding FEM. And their sensitivities are given by adjoint-direct method. Numerical examples show the algorithm performance. Optimum design and their performances for isotropic and anisotropic materials are compared.

12077
Fri·09:55·E

Topology optimization of optical band gap effects in slab structures modulated by periodic Rayleigh waves

Niels Aage,† Allan Gersborg and Ole Sigmund
Technical University of Denmark, Denmark†

This paper is concerned with topology optimization of a coupled optical and mechanical wave propagation problem in photonic crystals. It is motivated by the potential gain in functionality of optical devices where mechanical Rayleigh waves (travelling in the surface of the material) play a leading role. The practical applications cover novel optical modulators, switches and frequency shifters. Using the periodicity of the structure a unit cell analysis is used to calculate the response. The optical response is calculated using a 3D eigenvalue problem formulation of Maxwell's equations. The optomechanical interaction is modelled geometrically based on the amplitude field of the Rayleigh wave such that the optical state is computed using the eigenvalue formulation but with a geometrically distorted unit cell. The work uses COMSOL Multiphysics which is a modern finite element based modelling language.

Optimization of stepped beams and plates

11597
Fri·10:15·E

Jaan Lellep,† Tiina Kraav and Julia Polikarpus
University of Tartu, Estonia†

Beams and plates with rectangular cross-section are studied under the assumption that the thickness is piece-wise constant. Critical buckling loads of stepped composite columns are established. The columns subjected to the axial pressure are weakened with cracks emanating from re-entrant corners of steps. Minimum weight designs are established for given buckling load. An optimization technique is developed for circular plates of piece-wise constant thickness. The plates under consideration have been manufactured of an ideal elastic-plastic material obeying Tresca's yield criterion. Necessary optimality conditions are derived with the aid of the theory of optimal control. Obtained system of differential-algebraic equations is solved numerically in the case of the plate with single step of the thickness.

Structural optimization using evolutionary algorithm and data mining

11176
Fri·11:00·4

Ting-Yu Chen† and Yi Cheng
National Chung Hsing University, Taiwan†

With rapid progress of evolutionary computations, many global optimization methods are using evolutionary computations now. But evolutionary computations have a drawback of needing huge number of function evaluations. This makes it inadequate for structural optimizations. To overcome the difficulty this paper integrates evolutionary computation with data mining and approximate analysis to find the optimum solution in structural optimization. The approximate analysis is used to replace exact finite element analyses to save computational time. The data mining is used to guide the search in the feasible region to increase the chance of finding the global solution. These joint efforts can increase the efficiency and quality of structural optimization using evolutionary computation. The preliminary results show that the proposed method not only finds better solutions but also spends less computational time than other methods.

Level set approach for structural optimization

11775
Fri·11:20·4

Andrzej Myśliński
Systems Research Institute, Poland

This paper deals with the numerical solution of a structural optimization problem of an elastic body in unilateral contact with a rigid foundation. The contact problem with the prescribed friction is considered. The structural optimization problem consists in finding such topology and shape of the boundary of the domain occupied by the body that the normal contact stress along the contact boundary of the body is minimized. In the paper shape as well as topological derivatives formulae of the cost functional are provided using material derivative and asymptotic expansion methods, respectively. These derivatives are employed to formulate necessary optimality condition for simultaneous shape and topology optimization. Level set based numerical algorithm for the solution of the shape optimization problem is proposed. Numerical examples are provided.

Structural shape optimization by weight of NURBS with IGES file exchange

11363
Fri·11:40·4

Geol Choi† and Byung Kwak
Korean Advanced Institute of Science and Technology, South Korea†

The B-splines have been widely used for structural shape design in an interactive manner. Although non-uniform rational B-splines (NURBS) are capable of expressing complex geometries with a small number of control points by adopting the weights, they are rarely used because of difficulties of interfacing analysis tools with shape tools. IGES, the most widely used format for exchanging data among CAD/CAM/CAE systems, includes the weights of the control points as well as their positions and enables users to input the shape information to many commercial codes. This paper presents a method of shape design sensitivity analysis of structures with respect to the weight of control points using IGES file exchange, which has not been tried before. The finite element analysis is carried out by commercial code, ANSYS. Optimization is performed by the mathematical package, MATLAB. A motivating example is used to illustrate the feasibility of the method.

Manufacturing tolerant topology optimization for MEMS design

11483
Fri·12:00·4

Ole Sigmund
Technical University of Denmark, Denmark

In this paper we present an extension of the topology optimization method to include manufacturing uncertainties during the fabrication process. The application in mind is MicroElectroMechanical Systems (MEMS), where device performance is very sensitive to uncertainties during the manufacturing process. Under- and overetching during processing is indirectly modelled by image processing based "erode" and "dilate" operations and the optimization problem is formulated as a worst case design problem. In contrast to conventional reliability-based optimization approaches, the presented simplified method only results in an increase in CPU-time of a factor of three. Application of the method to the design of a microscopic compliant force inverter shows that it provides a manufacturing tolerant design with little if any decrease in structural performance.

SM19 :: Structural vibrations

Chairs: Marian Wiercigroch (UK) and Pedro Ribeiro (Portugal)

Tue	14:00–15:10	Room 6	Seminars
Tue	16:00–17:40	Room 5	Lectures
Thu	09:15–10:35	Hall C	Lectures
Fri	11:00–12:20	Hall B	Lectures

Phenomenological mapping method and mathematical analogy of hubrid system dynamics

10135
Tue·14:00·6

Katica Hedrih
University of Nis, Yugoslavia

Importance of phenomenological mapping and mathematical analogy increase with knowledge of numerous rare and unique phenomena in different kinds of hybrid system dynamics. Phenomenological mapping and mathematical analogy between multi pendulum systems, sandwich multi plate systems, sandwich multi beam systems as well as axially moving multi belt systems and mechanical chains with different coupling by standard light elements—elastic, hereditary or creep properties expressed by differential, integral, or fractional order differential operators are considered. Also, for homogeneous hybrid listed systems, the corresponding characteristic equations and solutions are obtained with corresponding periodic, as well as rheolinear modes in analytical as well as in graphical forms. Construction of Analytical dynamics of the hereditary discrete system by Goroshko and Hedrih and also Analytical dynamics of the creep discrete systems with standard light creep elements with constitutive relation expressed by fractional order derivative, open an analogy between these systems and systems in automatic control.

Elastoplastic and geometrically non-linear vibrations of beams by the p-version finite element method

10366
Tue·14:05·6

Pedro Ribeiro[†] and Gert van der Heijden
University of Porto, Portugal[†]

A model based on a Timoshenko beam p-version finite element is developed to analyse oscillations that are, simultaneously, elastoplastic and geometrically non-linear. The geometrical non-linearity is taken into account by the Von Kármán type of stress-strain displacement relation for beams and the plasticity is of the bilinear type, with strain hardening. The equations of motion are obtained using the principle of the virtual work and are solved in the time domain by an implicit Newmark method. Von Mises yield criterion is employed and the flow theory of plasticity applied; if the yield surface is passed at a Gauss point, the total plastic strain is incrementally determined. Numerical examples are carried out in order to demonstrate that the p-version element advocated has a number of advantages and to show the influence of the plastic and geometrically non-linear terms on the oscillations of beams.

Nonlinear parametric vibration of axially accelerating beams

10384
Tue·14:10·6

Li-Qun Chen† and Hu Ding
Shanghai University, China†

Nonlinear vibration is investigated in principal parametric resonance of an axially accelerating viscoelastic beam. The axial speed is characterized as a simple harmonic variation about the constant mean speed. The material time derivative is used in the viscoelastic constitutive relation. The method of multiple scales is applied to determine steady-state responses analytically. It is proved that the mode uninvolved in the resonance has no effect on the steady-state response. The differential quadrature schemes are developed to verify analytical results. It is demonstrated that the straight equilibrium configuration become unstable and a stable steady-state emerges when the axial speed variation frequency is close to any linear natural frequency. Numerical simulations are presented to examine the effects of the mean and the variation amplitude of the axial speed, the dynamic viscosity, and the nonlinear coefficients on the instability interval and the steady-state response amplitude.

Vibrations of a beam with a sliding mass

10832
Tue·14:15·6

Hassan Nahvi
Islamic Azad University, Khomeinishahr Branch, Iran

Vibrations of a structure may cause a freely sliding mass to slide in directions perpendicular to the direction of vibration. Sliding of the mass will change resonance frequencies of the structure. This non-linear effect may be utilized for vibration suppression. In this study an analytical model is developed to demonstrate essential features of a system with a sliding mass. It will be shown that small values of the mass rotary inertia has negligible effects on the system behavior, whereas, values larger than a critical value causes nontrivial changes in the system behavior. Frequency response curves for near-resonant harmonic excitations are provided and implications in the context of vibration damping are considered.

Gap waves propagating in layered piezoelectric material structures with initial stress

10860
Tue·14:20·6

Jianke Du,† Xiaoying Jin and Ji Wang
Ningbo University, China†

Shear horizontal gap waves propagating in layered piezoelectric structures with initial stress is investigated analytically. The boundary conditions imply that the displacement, shear stress, electric potential, and electric displacement are continuous across the interface between the layer and the substrate. The electrically open conditions at the interface between the air and the piezoelectric layer are applied to solve the problem. The phase velocity equation can be obtained and the velocity is numerically calculated and discussed in detail for different initial stresses in the piezoelectric layer. The numerical results show that the initial stress has remarkable effect on the phase velocity of the gap waves. We find that the phase velocity decreases with the increase of the initial stress.

Vibration and buckling behaviour of soft core sandwich plate using an improved higher order zigzag theory

11032
Tue·14:25·6

Bhrigu Singh,† Mihir Pandit and Abdul Sheikh
Indian Institute of Technology, Kharagpur, India†

An improved higher order zigzag theory is presented and it is applied to study the free vibration and buckling behaviour of soft core sandwich plates. The present theory exploits all the merits of layerwise theory including transverse flexibility of the core and at the same time enjoys the benefits of single layer theory in terms of computational efficiency. It satisfies both the conditions of transverse shear stress continuity at all the layer interfaces and transverse shear stress free conditions at the top and bottom surfaces of the plate. The through-thickness variation of in-plane displacements direction is assumed to be cubic, while transverse displacement varies quadratically within the core only. The core is modelled as a 3D elastic continuum. An efficient C^0 finite element is proposed for the implementation of the plate theory. The performance of the present formulation is shown by comparing the present results with the existing results available in literature.

Vibration localization in disordered periodically stiffened double-leaf panels

11045
Tue·14:30·6

Gui-Lan Yu,[†] Yue-Sheng Wang and Jian Lan
Beijing Jiaotong University, China[†]

This paper deals with the vibration localization in periodically stiffened double-leaf multi-span panels by transfer matrix method. The localization factor, defined as the smallest positive Lyapunov exponent, is calculated to describe the average rate of decay of the amplitude of deflection. The numerical results show that the propagation of vibration in periodic double-leaf panels exhibit passbands and stopbands. When the span-length is disordered, the vibration localization phenomenon occurs and is enhanced with the increasing disorder. With the flexural rigidity of the stiffeners increasing, the vibration localization first decreases, then increases and finally tends to be the situation of the single-leaf panel. For some particular values of the flexural rigidity, the vibration localization in low frequencies is very weak and therefore the vibration can travel through the whole double-leaf panels.

Magnetic damping of resonant rotor-bearing vibrations

11077
Tue·14:35·6

Wlodzimierz Kurnik[†] and Krzysztof Dziedzic
Warsaw University of Technology, Poland[†]

Resonant behavior of a rotor in hydrodynamic bearings with magnetic actuators is analyzed. Attention is focused on the influence of magnetic damping induced in the ferromagnetic core of a single magnetic actuator on the resonant behaviour of the rotor under constant gravity load and harmonic excitation. The dynamic relation between the magnetic field and magnetic induction in the core is described in form of a differential equation based on the hypothesis of magneto-rheologic analogy. Nonlinear magnetization curve reflecting magnetic saturation is included.

Difference resonances in a controlled van der Pol–Duffing oscillator

11129
Tue·14:40·6

Jinchen Ji
University of Technology, Sydney, Australia

The trivial equilibrium of a controlled van der Pol–Duffing oscillator with nonlinear feedback control may lose its stability via a non-resonant interaction of two Hopf bifurcations when two critical time delays corresponding to two Hopf bifurcations have the same value. Such an interaction results in a non-resonant bifurcation of co-dimension two. In the vicinity of the non-resonant Hopf bifurcations, the presence of a periodic excitation in the controlled oscillator can induce difference resonances in the forced response, when the frequency of the external excitation and the frequencies of the two Hopf bifurcations satisfy a certain relationship. It is found that the additive resonance response of the controlled system may exhibit quasi-periodic motions on a 3-dimensional torus consisting of three frequencies, which are the frequencies of two bifurcating solutions and the frequency of the excitation. Illustrative examples are given to show the quasi-periodic motions.

Chaotic vibrations of a post-buckled cantilevered beam constrained by a stretched string at the top end

11234
Tue·14:45·6

Ken-ichi Nagai,† Shinichi Maruyama, Kota Muto and Takao Yamaguchi
Gunma University, Japan†

Analytical procedure and the corresponding results are presented on the chaotic vibrations of a post-buckled cantilevered beam constrained by a stretched string at the top end. The dynamical model involves nonlinear geometrical coupling between the deformation and the axial force in the boundary condition. The mode shape function proposed by the senior author is introduced to reduce the governing equation to the nonlinear ordinary differential equations in multiple-degree-of-freedom system by the modified Galerkin procedure. The chaotic responses are calculated numerically with the approaches of single-degree-of-freedom and of multiple-degree-of-freedom. Higher modes of vibration play very important roles both in the chaotic behavior and in the periodic response.

Proposals for visualising the evolution of approximate analytical solutions in engineering dynamics

11240
Tue·14:50·6

Matthew Cartmell† and David Forehand
University of Glasgow, UK†

It is generally accepted that analytical solutions to problems in engineering dynamics are desirable in cases where they can be obtained. These are usually problems in which reduced order modelling can be reasonably applied, where nonlinearity is prevalent, and where periodicity can be observed. It is proposed that the evolution of such solutions, and therefore the history of inheritance of the terms within the solution, may provide a useful adjunct to the information conventionally obtained from such solutions, provided it can be visualised in a meaningful way. This paper presents proposals for codifying algebraic evolution and inheritance within a candidate approximate analytical solution procedure, in this case the method of multiple scales, and sets the scene for visualisation of these normally hidden features. The paper discusses two different procedural models for encoding and summarises their potential for information enhancement.

Nonlinear transient vibration of an axially moving string with an attached traveling oscillator under wind excitations

11295
Tue·14:55·6

Yuefang Wang† and Lefeng Lü
Dalian University of Technology, China†

Axially moving continua are found in many engineering appliances that transport material and energy. The recent concern is the transverse vibration of axially moving systems with a travelling oscillator. In this case, an oscillator is attached to the moving continua through a spring and a damper. The linear vibration was solved by various methods. However, no previous work was found for nonlinear transient response of moving continua with coupled traveling oscillator to the knowledge of the authors. In this paper, the nonlinear transient vibration of an axially moving string with an attached travelling oscillator is investigated. This is parametric vibration problem with periodically variant coefficient which is solved numerically. We focus on the transient resonant response when the natural frequency of the oscillator is close to the frequency of the string. The effect of the geometrical nonlinearity due to large deformation and the interaction inside the system are presented.

Stochastic data-based representation of uncertain complex non-linear systems

12071
Tue·15:00·6

Sami Masri,† Miguel Hernandez-Garcia, Felipe Arrate and Roger Ghanem
University of Southern California, USA†

This paper presents a study of a general methodology for representing and propagating the effects of uncertainties in complex nonlinear systems through the use of a reduced-order, reduced-complexity, model-free representation, that allows the estimation through analytical procedures of the uncertain system's response bounds when it is excited by a different dynamic load than the one used to identify it. A nonparametric identification approach based on the use of the Restoring Force Method is employed to obtain a stochastic model of the nonlinear system of interest. Subsequently, the reduced-order stochastic model is used, in conjunction with polynomial chaos representations, to predict the uncertainty bounds on the nonlinear system response under transient dynamic loads.

PDF solution to nonlinear oscillators excited by Gaussian and Poisson white noises

12104
Tue·15:05·6

Hai Zhu,† Guo Er, Kun Kou and Vai Iu
University of Macau, Macau†

Stationary probabilistic solution to nonlinear oscillators excited by Gaussian and Poisson white noises is analyzed in this paper. The joint probability density function (PDF) of the displacement and velocity is governed by the generalized Fokker–Planck–Kolmogorov (FPK) equation. Exponential polynomial closure (EPC) method is adopted to solve the generalized FPK equation. The solution of the generalized FPK equation is assumed to be an exponential function of polynomials in state variables. Special measure is taken so that the generalized FPK equation is satisfied in the average sense of integration with the assumed PDF. The problem of determining the unknown parameters in the approximate PDF finally results in solving simultaneous nonlinear algebraic equations. Illustrative example shows that the PDFs obtained with EPC method agree well with the simulated results with the polynomial order being 6, especially in the tail regions, which is important for reliability analysis.

Normal vibration modes of a slender beam on elastic foundation with unilateral contact

10873
Tue·16:00·5

Carlos Mazzilli† and Stefano Lenci
University of So Paulo, Brazil†

The normal modes and the natural frequencies of a semi-infinite Bernoulli–Euler beam resting on a unilateral elastic foundation of the Winkler type are determined. Whenever the beam is set to vibrate, the nonlinearity of the soil behaviour induces a motion of the touchdown point, which separates the suspended part from the rest of the beam. The problem thus falls in the realm of moving-boundary problems, and it is transformed into a fixed-boundary one by an appropriate change of coordinates. The natural frequencies are computed by means of the multiple scales method, and it is shown that, due to the energy dissipated by radiation, there are no longer natural frequencies over a certain critical threshold.

Forced response of waveguides from finite element analysis

10908
Tue·16:20·5

Brian Mace,† Yoshiyuki Waki and Michael Brennan
University of Southampton, UK†

The propagation of waves in a structure is of interest for many applications, especially at higher frequencies. In simple cases, analytical expressions for the dispersion equation and forced response can be found. For complicated structures, such as laminates, cylinders and tyres, analytical approaches are complicated at best. In such cases finite element analysis can be used to predict time harmonic response: a small segment of the structure is modelled, periodicity conditions applied and the resulting dynamic stiffness matrix yields the dispersion relations. This paper describes the application of the wave/finite element method to forced response calculation. Both point and spatially distributed excitations are considered. The example of the forced response of an automotive tyre is presented.

An inverse dynamic approach of statistical health monitoring of structure from limited noisy data

11149
Tue·16:40·5

Debasish Bandyopadhyay† and Sriman Bhattacharyya
Indian Institute of Technology, Kharagpur, India†

Inverse dynamic approach to improve the mathematical models of the dynamics of structure from measured responses is important tool in structural health monitoring. But uncertainties, particularly in terms of measurement noise might lead to unreliable assessment. The dynamic measurement at all its degrees of freedom is also practically not feasible. In this paper, a statistical health monitoring technique of structure based on limited measured modal data with random noise is developed adopting inverse dynamic approach. System Equivalent Reduction Expansion Process is employed to simulate the full modal data. Least square technique is adopted to solve the error equation of identification. The statistical distributions and the probability of damage existence of structural properties for each element are derived with this model updating process. The proposed method is demonstrated with a frame problem using numerically simulated limited noisy modal data measured at few degrees of freedom.

Nonlinear vibrations of an annular hyperelastic membrane

11196
Tue·17:00·5

Paulo Gonçalves† and Renata Soares
Catholic University, PUC-Rio, Brazil†

The aim of the present work is to investigate the nonlinear vibration response of a pre-stretched annular hyperelastic membrane subjected to finite deformations. The membrane is composed of an isotropic, homogeneous, incompressible and hyperelastic material, which is modeled a neo-Hookean material. First the solution of the membrane under a uniform radial stretch is obtained. Then the equations of motion of the pre-stretched membrane are derived. From the linearized equations, the natural frequencies and mode shapes of the membrane are obtained analytically. Then the natural modes are used to approximate the nonlinear deformation field using the Galerkin method. Reduced order models are derived and the results compared with the results evaluated for the same membrane using a nonlinear finite element formulation. Excellent agreement is observed. The results show the strong influence of the stretching ratio on the linear and nonlinear oscillations of the membrane.

Damage identification in multilayer composite structures using Lamb stress waves

10242
Tue·17:20·5

Wieslaw Ostachowicz† and Pawel Kudela
Polish Academy of Sciences, Poland†

Delamination is a major problem in multilayer composite structure. Among various techniques, a health monitoring system based on PZT transducers and Lamb wave propagation seems to be a promising method for a quick and continuous inspection of composite structures. However, there is lack of models which enable to explain wave behaviour in stiffened composite structures with delamination. For this reason spectral finite element models of hat-stiffened plates with delamination at the skin-stiffener interface have been developed. It is shown how such models can explain the behaviour of propagating waves at disbonding region. It can be seen that visualisation of wave scattering leads to damage identification. Numerical simulations provide helpful information about dispersion, mode conversion and wave scattering from stiffeners and boundaries. It can allow one to optimise excitation signal parameters and sensor placement, as well as enable analysis of signals reflected from damage.

Guided waves damage detection in beams utilising Bayesian artificial neural network model class selection

11257
Thu·09:15·C

Ching Ng,† Martin Veidt and Chin Liew
The University of Queensland, Australia†

This paper presents a damage detection methodology utilising an Artificial Neural Network (ANN) pattern recognition approach to identify the location and severity of damages in beams. The Bayesian model class selection method is employed to determine an optimum ANN model, hence avoiding subjective judgement during the ANN design process. Simulated first order longitudinal guided waves signals for beams with different damage locations and severities are preprocessed using discrete wavelet transformation to reduce ANN processing time and are then used as input patterns to train the ANN. The trained network is employed to identify unknown damages in beams with simulated damage cases. The investigation shows that the Bayesian model class selection results in the design of an ANN model that performs very well in regard of pattern matching and generalisation capabilities.

Bifurcation patterns of a whirling transported string

11389
Thu·09:35·C

Gert van der Heijden† and Barrie Fraser
University College London, UK†

We present a comprehensive analysis of the quasi-stationary solutions of a rotating string drawn at constant speed through two fixed guide eyes. Motivation comes from textile applications such as high-speed spinning and unwinding from a package. The boundary-value problem without the effect of air drag can be solved explicitly. An infinite number of ballooning modes (described by elliptic functions/integrals) bifurcate from the straight configuration. A critical speed occurs when the through-put speed becomes equal to the speed of transverse waves in the string. The equation also allows for solutions at supercritical speeds. In the presence of air drag no stationary whirling solutions exist. However, if one guide eye is replaced by an open annulus so that the string moves along a circle (modelling the boundary conditions of certain unwinding problems) then solutions do exist and we find an interesting unfolding of the bifurcation diagram with interactions between the various modes.

Experimental unfolding and reduced order model in the complex dynamics of a sagged cable

11411
Thu·09:55·C

Giuseppe Rega† and Rocco Alaggio
Sapienza Università di Roma, Italy†

A profitable feedback between experiments and theory allows to unfold the complex forced dynamics of a sagged cable triggered by a divergence-Hopf codimension two bifurcation. Exploiting hints provided by a reduced order theoretical model, systematic investigation of a thermally conditioned experimental setup allows to characterize the most robust classes of motion (in terms of dimensionality and cable proper orthogonal modes) and variable transition scenarios of system response (via bifurcation diagrams and spectra of singular values of measurement results). Considering the temperature as a controllable parameter besides excitation amplitude and frequency, allows to qualitatively refer the experimental unfolding of regular and nonregular dynamics to the theoretical unfolding of d-H bifurcation normal form with D4 symmetry. Experimental outcomes and features of transition to low-dimensional homoclinic chaos are complemented with analytical/numerical results of the reduced order model.

Subcritical flutter in the problems of acoustics of friction

10157
Thu·10:15·C

Oleg Kirillov
Technische Universitaet Darmstadt, Germany

Linearized models of rotating elastic bodies of revolution possess a spectrum that forms a mesh in the plane ‘frequency’ versus ‘gyroscopic parameter’ with double semi-simple eigenfrequencies at the nodes. In contact with the friction pads, the rotating media, for example the singing wine glass or the squealing disc brake, start to vibrate due to subcritical flutter instability. In the present paper a sensitivity analysis of the spectral mesh is developed for explicit predicting the onset of the friction-induced instabilities. The key role of indefinite damping and non-conservative positional forces in the development and localization of the subcritical flutter is clarified. It is shown that the instability scenarios, revealed in the general two-dimensional case, can take place also in more complicated finite-dimensional and distributed models of rotating symmetric bodies in frictional contact.

VIV of vertical offshore riser in lock-in: low-dimensional model

10567
Fri·11:00·B

Marian Wiercigroch,† Narakorn Srinil and Marko Keber
University of Aberdeen, UK†

A low dimensional model of Vortex Induced Vibration (VIV) for a vertical flexible offshore riser in the lock-in conditions is constructed and analysed. The structure is modelled as an Euler–Bernoulli beam excited at modal frequencies by discrete vortices in the form of wake oscillators of Van der Pol type. By applying the method of Nonlinear Normal Modes we reduced the problem to a single nonlinear oscillator. The dynamics of the wake oscillator was calibrated using a CFD simulation of the flow surrounding a moving cylinder. The undertaken nonlinear dynamics analysis reveals details of the resonant structure of the coupled system which can be divided into 3 different regions: resonant behaviour (lock-in), transition to lock-in and quasi-periodic responses. We paid a particular attention to the onset to lock-in.

Dynamic analysis of an automatic transmission parking mechanism

10469
Fri·11:20·B

Jeku Jeyakumaran† and Nong Zhang
University of Technology, Sydney, Australia†

This paper describes a simulation model capable of predicting the impact and abrading characteristics of the parking mechanism used in an automatic transmission. Several linear and nonlinear mathematical models are developed to satisfactorily reproduce the dynamic characteristics observed in vehicle tests. Mathematical representation of the parking mechanism assembly is based on modelling the local contact deformation of the components combined with the vibrations of the parking pawl predicted by Euler's beam theory. Impact and contact conditions are formulated from first principles to include the effects of elasticity, damping and friction. Ratcheting engagement speeds predicted by the simulation are in very good agreement with the vehicle abuse tests. Simulation results provide insight into various design parameters relevant to the durability, and noise and vibration characteristics of the parking mechanism

Amplitude reduction of self-excited micro-cantilever probe of atomic force microscope

10514
Fri·11:40·B

Hiroshi Yabuno,† Masaharu Kuroda, Kiwamu Ashida and Takeshi Kobayashi
University of Tsukuba, Japan†

Amplitude control of a self-excited micro-cantilever probe of atomic force microscope (AFM) is theoretically and experimentally discussed for realizing high-resolution imaging of biological materials. The utilization of self-excited oscillation makes it possible to observe the surface of the materials in a liquid environment where the quality factor Q of the probe is very low. Also, to give no damage to the soft biological materials, i.e., for non-contact measurement, small steady state amplitude of the self-excited cantilever probe has to be realized. By applying nonlinear feedback control, micro-cantilever probe which behaves as van der Pol Oscillator is theoretically designed and the small steady state amplitude is experimentally confirmed by using our own making AFM.

Classification of non-smooth bifurcations for a friction oscillator

11338
Fri·12:00·B

Hans Troger,† Alois Steindl and Andreas Teufel
Vienna University of Technology, Austria†

During the last quater of the 20th century for several classes of smooth parametrized dynamical systems significant theorems classifying all qualitatively different bifurcations have been proved (see, for example, the books by V. I. Arnold, Ph. Holmes, J. Guckenheimer, M. Golubitsky). These efforts have been extended by Y. Kuznetsov and his co-workers to planar non-smooth systems of Filippov type, for which a complete classification of all codimesion 1, that is one-parameter, bifurcations is given. Since to this class belong friction oscillators with a non-smooth friction law the classification is of great practical importance in Mechanics because it allows to see whether in an engineering analysis of a friction oscillator all possible bifurcations of a certain class are found. The aim of this lecture is to analyse the relevant bifurcation behavior of a self-excited friction oscillator taking into account that it is a Filippov systems.

SM20 :: Viscoelasticity and creep

Chairs: Alan Cocks (UK) and George Voyiadjis (USA)

Tue	14:55–15:05	Room 1	Seminars

Bases and advances of the synthetic theory of irreversible deformation

11073
Tue·14:55·1

Endre Ruszinko
Budapest Polytechnic, Hungary

A new theory, the synthetic theory of irreversible deformation, is presented. This theory, which is concerned with small irreversible strains of work-hardening materials, combines Sander's variant of flow plasticity theory and the Batdorf–Budiansky slip concept. In terms of synthetic theory, a number of non-classical problems of plastic and creep deformation have been solved. The main advantages of this theory are that its constitutive equations account for real physical processes occurring in a body at irreversible deformation, macro strains are determined on the basis of the analysis of strains generated on the micro level of crystal structure of metal, and the formulae for a creep and plastic strain are derived from the sole constitutive equation. The results obtained in terms of synthetic theory are in agreement with experimental data and are applicable to solving a number of boundary-value engineering problems.

An advanced rapid three-dimensional modeling technology for asphalt concrete

11856
Tue·15:00·1

Xinhua Yang,† Yong Ye, Chuanyao Chen and Rui Xu
Huazhong University of Science and Technology, China†

An advanced rapid three-dimensional packing technology applicable for modeling asphalt concrete is presented in this paper. A polyhedron is generated by extending an arbitrary triangular basis, and it can be regarded as a single aggregate after passing through convex control and sharpness judgment. Amount of random aggregates generated circularly by this method in accordance with an actual grading curve are stored in an aggregate base. After that, a cylindrical packing region is created, and then aggregates are randomly put in it one by one according to the equiprobable principle. Superposition between nearby aggregates can be avoided by the overlap judgment. Finally, several asphalt concrete samples with different aggregate volume fraction are modeling. Their viscoelasticity and creep are probed under a constant compressive load and the influences of aggregate volume fraction are carefully investigated.

FSM01 :: Acoustics

Chairs: Roger Ohayon (France) and Nigel Peake (UK)

Mon	16:25–17:45	Hall B	Lectures
Tue	15:10–15:15	Room 5	Seminars
Fri	09:15–10:35	Hall B	Lectures

Silent embedded boundaries for combustion noise simulation

10506
Mon·16:25·B

Wolfgang Schröder† and Thanh Bui
Aerodynamisches Institut, Germany†

The often encountered discrepancy in the characteristic scales in the flow and sound field leads to the hybrid concept, i.e., the separation of the noise analysis from the flow field or the combustion process. In sound propagation problems particular attention has to be paid to the formulation of boundary conditions since their accurate definition has large effects on the sound field. This extreme sensitivity of the sound field against perturbations at the boundaries holds at outer and at inner boundaries, such as those defined in the hybrid approach. Due to the discontinuity in the vorticity distribution numerical noise is generated at these embedded boundaries that can remarkably falsify the acoustic field. A solution to this problem will be discussed in the context of combustion noise.

The effect of non-axisymmetric flow disturbances on the sound generation in the hole-tone feedback cycle

10414
Mon·16:45·B

Mikael Langthjem† and Masami Nakano
Yamagata University, Japan†

The hole-tone feedback cycle, also known as Rayleigh's bird-call, is considered. A numerical method for analyzing the influence of non-axisymmetric perturbations of the jet on the sound generation is described. In planned experiments these perturbations will be applied at the jet nozzle via piezoelectric actuators, placed circumferentially inside the nozzle at its exit. The mathematical model is based on a three-dimensional vortex method. The nozzle and the holed end-plate are represented by quadrilateral vortex panels, while the shear layer of the jet is represented by vortex rings, composed of vortex filaments. The sound generation is described mathematically using the Powell–Howe theory of vortex sound. The aim of the work is to understand the effects of a variety of flow perturbations, in order to control the flow and, most important, the accompanying sound generation.

Models for acoustic propagation through turbofan exhaust flows: lined ducts

10571
Mon·17:05·B

Nigel Peake† and Ben Veitch
University of Cambridge, UK†

Turbomachinery noise is an important problem for modern civilian aircraft, and it is perhaps the field radiating into the rearward arc from the bypass duct which causes the greatest engineering concern. This noise is scattered by the trailing edges of the nacelle and the jet exhaust, and interacts with the shear layers between the external flow, bypass stream and jet, en route to the far field. In this paper we solve a model problem which represents for the first time a key feature of the real geometry, namely that the jet nozzle protrudes a finite distance beyond the end of the nacelle. This involves a matrix Wiener-Hopf problem, which we solve using Abrahams' Pade approximant method

to factorise the kernel. We consider both hard-walled ducts (for which the matrix is 2 by 2) and acoustically lined ducts (3 by 3 matrix). Full results for the far field sound, including the effects of mean flow shear, will be presented.

Sound generation in flows with steady heat communication

10728
Mon·17:25·B

Nader Karimi,† William Moase, Michael Brear and Nader Karimi
University of Melbourne, Australia†

This paper investigates the generation of sound in quasi-one-dimensional, non-diffusive flows with steady heat communication. It is argued that sound generation by steady heat communication can be comparable to sound generation by the well established mechanism of the acceleration of density inhomogeneities. The existence of such a mechanism is first shown analytically through a properly formulated wave equation and the conservation of acoustic energy. The problem is then simulated numerically. Two cases are considered: a one dimensional flow in which the heat communication accelerates the flow and a quasi-one dimensional flow where the area variation exactly balances the effect of heat communication such that there is no acceleration of the steady flow. In both cases, acoustic forcing of the inhomogeneous region generates or attenuates sound, even though there is no unsteady heat addition, and in the later case, no acceleration of the steady flow.

AGILD WMT ray-tracing interactive tomography

11215
Tue·15:10·5

Jianhua Li,† Chien-Chang Lin, Ganquan Xie and Michael Oristaglio
GL Geophysical Laboratory, USA†

A wavelength matching topology (WMT) interactive tomography is developed to generate advanced global integral and local differential (AGILD) finite element mesh. The wavelength matching topology and the curve ray tracing are combined to construct the AGILD FEM Ray Tracing tomography forward modeling and inversion algorithm. The rays are accurately traced using the known velocity expression in the current element instead of in-layered or stratified medium. The interactive tomography provides a useful tool to analyze acoustic mechanical and macro and micro multiple optical measurement sites, materials laboratory experiment and exploration surface to surface, surface to points, surface to borehole, crosshole, and multiple points and holes data. It is very useful to develop next generation wave propagation algorithm for computational mechanics, geophysics, biomedical sciences, hydrodynamics. It can be used in geophysical subsurface tomography, nondestructive testing for structure health.

Wolf killing: the subtle problem of controlling cello string/body coupled resonances

11935
Fri·09:15·B

Antunes Jose† and Octavio Inacio
Insituto Tecnologico e Nuclear, Portugal†

A common annoying phenomenon which arises with most cellos is the so-called “wolf note”. This is a warbling sound stemming from a severe interaction between the string and the body motions, coupled at the instrument bridge. Instrument builders have found that adding a small auxiliary mass on the so-called “dead” side of the string often inhibits the wolf phenomenon. However, the tuning of such “wolf-eliminators” is laborious and often ineffective, as the physical role of such devices is poorly understood. In this paper we present for the first time a fully coupled string/body/wolf-eliminator model for an actual cello. Numerical simulations of the friction-excited regimes of the bowed string highlight how the wolf note emerges. Computations using several wolf-eliminator masses and locations help to elucidate the dynamical behaviour of these devices.

Acoustic properties of dry and saturated porous media

11161
Fri·09:35·B

Pierre Adler,[†] Iryna Malinouskaya, Valeri Mourzenko, Igor Bogdanov and Jean-Francois Thovert
UPMC-Sisyphe, France[†]

The acoustical properties of porous media are addressed in the general framework of homogenization theory, by assuming that the typical pore scale is small compared to the wave length, and by applying the successive expansions of the formalism of Auriault and Boutin (1993). For dry media, the celerity of plane compressive or shear waves can be determined, as well as the correction to polarization, the celerity dispersion and the attenuation due to Rayleigh scattering. Various kinds of model media are studied, and a few real materials which have been characterized by Xray microtomography. In saturated media, the acoustical behavior is governed by the elastic equations in the solid phase and by the Navier-Stokes equations in the interstitial fluid. The dynamic permeability and the compressive and shear wave celerities are determined for the same media as in the dry case.

Acoustics of streaming: a mechanism of noise generation in subsonic jets

11554
Fri·09:55·B

Xuesong Wu[†] and Patrick Huerre
Imperial College London, UK[†]

This paper presents a possible fundamental physical mechanism by which instability waves generate sound waves in subsonic jets. It involves a wavepacket of a pair of helical modes with nearly the same frequency but opposite azimuthal wavenumbers, which modulates simultaneously in space and time. The helical modes interact to generate a strong three-dimensional, slowly modulating, mean-flow distortion. We show that this mean-flow distortion radiates sound waves to the far field. The emitted sound is of very low frequency, with characteristic time and length scales being comparable with those of the wave envelope, and is determined by using a matched-asymptotic-expansion approach. Parametric studies indicate that the acoustic field is characterised by a single-lobed directivity pattern beamed at an angle about 45–60 degree to the jet axis, and a broadband spectrum centred at a Strouhal number about 0.07 to 0.25. These gross features are broadly in agreement with experiments.

The "two-phase sound" of cheering champagne glasses

11899
Fri·10:15·B

Debut Vincent[†] and José Antunes
Institute of Nuclear Technology, Portugal[†]

To avoid excessive flow-induced vibrations in industrial components operating in two-phase flow, the analysis and understanding of dissipation mechanisms is of prime importance. Several experimental studies revealed the strong dependence of two-phase damping on the characteristics of the two-phase flow. As a step toward such fundamental concept, we consider to investigate the fluid-structure interaction of a champagne glass filled with a bubbly liquid. The vibro-acoustical model is based on a 1D-pipe filled with a bubbly liquid which couples two pistons located at both ends of the pipe. Taking into account the mixture compressiblity and dissipation, the coupled problem is solved by projection on the acoustical basis of the close-closed pipe. A set of modal ODEs is obtained from which the eigenvalues and eigenvectors are computed. Two-phase damping of the vibro-acoustical system is found to vary with the void fraction as observed in experiments.

FSM02 :: Biomechanics

Chairs: Stephen Cowin (USA) and Ross Ethier (UK)

Mon	14:00–16:00	Room 2	Lectures
Mon	16:25–17:45	Room 2	Lectures
Tue	10:40–12:40	Room 2	Lectures
Tue	16:00–17:40	Room 2	Lectures
Wed	10:40–13:00	Room 2	Lectures
Thu	09:15–10:35	Room 2	Lectures
Thu	14:00–14:50	Room 11	Seminars

Real-time simulation of non-linear tissues by model reduction techniques

10579
Mon·14:00·2

Francisco Chinesta,† Siamak Niroomandi, Iciar Alfaro and Elias Cueto
LMSP-SERAM ENSAM, France†

In this paper we introduce a new technique for the real-time simulation of non-linear tissue behavior based on a model reduction technique known as Proper Orthogonal (POD) or Karhunen–Loève Decompositions. The technique is based upon the construction of a complete model (using Finite Element modelling or other numerical technique, for instance, but possibly from experimental data) and the extraction and storage of the relevant information in order to construct a model with very few degrees of freedom, but that takes into account the highly non-linear response of most living tissues. We present its application to the simulation of palpation a human cornea and study the limitations and future needs of the proposed technique.

Thin films of transversely isotropic fluid: applications to collagen gels

10808
Mon·14:20·2

Edward Green† and Avner Friedman
The Ohio State University, USA†

Motivated by the aim of modelling the mechanical behaviour of biological gels (such as collagen gels) which have a fibrous microstructure, we consider the flow of a thin two-dimensional film of incompressible, transversely isotropic viscous fluid. Two regimes are considered: extensional flow, and squeezing flow of the fluid between two rigid plates. Neglecting inertia, gravity and surface tension, in each regime leading-order equations are derived from a perturbation expansion of the full flow problem in powers of the (small) inverse aspect ratio. Special cases in which the solution may be determined explicitly are considered and the physical interpretation of the results is discussed.

Partitioned FEM/FVM coupling for cardiac fluid-structure interaction with a macroscopic composite approach

10844
Mon·14:40·2

Sebastian Krittian,† Herbert Oertel and Torsten Schenkel
University of Karlsruhe, Germany†

Statistically, heart disease has been the major cause of death in the recent past which emphasises the need for numerical models representing cardiac conditions. For the first time, the prescribed geometry movement of the existing KaHMo CFD heart model has now been replaced by a novel soft-tissue composite approach. The matrix and fibre arrangement represents the macroscopic myocardial behaviour using the theory of finite elasticity. In order to gain a better understanding of the structural influence on the flow pattern, the application of a newly implemented partitioned

coupling combination for cardiac fluid-structure interaction is of utmost importance. Results of first flow simulations with fluid-structure interaction help to further understand the hydro-elastic blood/soft-tissue interaction. Within this work both the novel myocardial composite approach and the new-implemented coupling procedure concept are explained.

Constitutive modeling of the stress–strain behavior of F-actin filament networks

10995
Mon·15:00·2

Jeffrey Palmer[†] and Mary Boyce
Massachusetts Institute of Technology, USA[†]

The stress-strain behavior of F-actin networks, important to many cellular functions, is modeled via a microstructurally-informed continuum mechanics approach. The force-extension behavior of the individual filaments is captured with a new analytical expression of the MacKintosh worm-like chain relationship for semiflexible filaments. The filament expression is used in the Arruda–Boyce eight-chain network model to capture the 3D stress-strain behavior, quantifying the effects of isotropic network prestress and tracking microstructural stretch and orientation states during large deformations. The network model captures the initial stiffness of the network as well as the nonlinear strain stiffening observed at large stresses in shear microrheological data of bundled/unbundled in vitro networks. The 3D model is extended to capture the poroelastic and viscoelastic behavior of cytoskeletal networks as well as contributions from cross-links and enthalpic stretching of cytoskeletal filaments.

Investigations of invariant based constitutive laws for modelling myocardial mechanics

11109
Mon·15:20·2

Holger Schmid,[†] Yikan Wand, Jesse Ashton, Alexander Ehret, Sebastian Krittian, Martyn Nash, Peter Hunter and Mikhail Itskov
University of Aachen, Germany, Germany[†]

Recent studies have shown the suitability of various constitutive equations for modelling the orthotropic behaviour of myocardium under simple shear. The constitutive equations were mostly formulated with respect to the Green-strain components. However, other laws exist which are based on invariant theory. As a first step these have been investigated under the assumption of a homogeneous simple shear deformation to model the underlying experimental data. Furthermore, they have also been investigated in finite element studies. The results of both studies are presented and compared. It is concluded that an exponential Fung-type law as well as specific polyconvex form are most suitable to model myocardial mechanics under simple shear.

Resonance in the cochlea with wave packet pseudomodes

11125
Mon·15:40·2

Dominik Obrist[†] and Peter Schmid
ETH Zurich, Switzerland[†]

Acoustic stimulation leads to a fluid flow inside the cochlea which deflects the basilar membrane. The resonance solutions, i.e., the steady-state responses of the basilar membrane due to harmonic stimulation, have the shape of wave packets. Their location depends on the stimulation frequency. This is the motivation for studying the cochlear dynamics on the basis of the theory of wave packet pseudomodes. Wave packet pseudomodes are asymptotically good approximations to eigenmodes. They are closely related to pseudospectra which are used successfully for studying nonnormal dynamical systems. The theory of wave packet pseudomodes allows us to derive relatively simple relations for predicting the location (and the local wavenumber) of the wave packets directly as a function of the stimulation frequency. We demonstrate the quality of these predictions by comparing them to numerical solutions.

Biomechanical models of epidermal wound closure in embryos

11126
Mon·16:25·2

Alexander Sadovsky† and Frederic Wan
University of California, Irvine, USA†

Epidermal wounds in mammalian embryos are an excellent biological model of successful wound repair. A central role in the repair is ascribed to the purse string phenomenon. It consists of the formation of an actin cable around the wound, which contracts as the wound closes. To investigate quantitatively whether the phenomenon alone can provide wound closure, we model it mathematically as a biomechanical process, with the epidermis a 2D deformable medium. The model has two main conceptual components. The first is a mechanism for the detection and assessment of the wound, based on a hypothetical cell-cell signaling system. The second component is a tensorial formulation of the purse string phenomenon. Our numerical simulations suggest that, in the absence of cell proliferation, migration, and differentiation, the purse string phenomenon will close a wound in an epidermis that is a linearly viscous fluid or a nonlinearly viscoelastic solid.

Longterm prediction of bone remodelling effect around implant

11152
Mon·16:45·2

Vaclav Klika,† Frantisek Marsik and Ivan Landor
Czech Academy of Sciences, Czech Republic†

The great unknown in the joint-replacement problem is how will the bone respond in terms of remodelling to new stress-strain field in bone after the replacement. In other words, the joint implant creates a very new conditions for the natural remodelling processes. Usually, there is a considerable resorption in the vicinity of an implant but in some cases there is also a significant deposition of bone tissue in specific sites that strengthens the imposition of prosthesis in bone. We studied bone remodelling using our biomechanical model that is in keeping with the facts that the driving force of the remodelling process is the dynamic loading but also with the substantial influence of the biochemical control - osteoprotegerin (OPG) concentration. Clinical observations shows that in the course of time the denser regions in the bone shift in the distal direction towards the implant tip. This type of results is also obtained using our bone remodelling model.

Mechanics of memory and learning

11284
Mon·17:05·2

Taher Saif,† Akira Chiba, Jie Sung, Scott Siechen and Shengyuan Yang
University of Illinois at Urbana-Champaign, USA†

Memory and learning in animals is mediated by neurotransmission at the synaptic junctions (end point of axons). Neurotransmitters are carried by synaptic vesicles, which cluster at the junctions. A central dogma in neuroscience is that clustering is the result of a complex biochemical signaling process. We show, using nano scale force sensors and fruit fly (Drosophila) embryo nervous system, that mechanical tension in axons is essential for clustering. Without tension, clustering disappears, but reappears with application of tension. Nature maintains a rest tension of 1 nN in axons of Drosophila embryos. Under a fixed applied stretch, the tension in the axon relaxes over time to 1 nN. A stretched axon, when released, recovers its original length and the rest tension over time. We propose a mechanistic model to interpret the results. The model predicts the experimental observations, and suggests that the axons possibly maintain the rest tension by a passive actin-myosin interaction.

Multiscale analysis of the human aortic valve

12000
Mon·17:25·2

Mohammad Mofrad† and Eli Weinberg
University of California, Berkeley, USA†

In the heart's aortic valve, maintenance of a healthy state and transition to disease states are modulated by the cells in the valve. The cells found within the valve leaflets are valvular interstitial cells and those found on the fluid-facing surfaces are endothelial cells. Both types of cell are known to respond to their mechanical state; that is, the stresses and deformations imposed on a cell by its surrounding environment. We present a set of simulations to examine these mechanical states of the cells as the valve goes through its opening and closing cycle. We have created a simulation at each of the cell, tissue, and organ length scales and introduced a system of reference configurations to link the scales. Each model and the set of multiscale simulation are verified against experimental data. This multiscale simulation approach allows us to accurately predict the dynamic, three-dimensional mechanical state of cells throughout the valve.

The intervertebral disc as a saturated porous material

11320
Tue·10:40·2

Nils Karajan† and Wolfgang Ehlers
University of Stuttgart, Germany†

This chapter is concerned with the process of choosing an appropriate model to simulate the behaviour of intervertebral discs (IVDs). Generally, the choice of a multi-phasic theory makes sense due to the inherent porous microstructure of the tissue. However, such models can be formulated at any complexity level concerning the number of constituents and their constitutive equations. Keeping this in mind, an extended biphasic formulation is applied which includes the inhomogeneously distributed properties of a nonlinear and anisotropic hyperelastic solid, a viscous interstitial fluid, and an osmotic pressure contribution. In order to point out the influence of the chosen constitutive assumptions on the overall behaviour, a numerical sensitivity analysis of the involved parameters is carried out using an L4-L5 bending experiment. Thereafter, two simulations of the lumbar spine in flexion are presented illustrating the influence of a stiffened L4-L5 motion segment on the upper IVD's.

Mechanics of traumatic brain injury at multiple length scales

11371
Tue·11:00·2

Johannes van Dommelen,† Rudy Cloots, Matej Hrapko, Gerrit Peters, Jac Wismans and Marc Geers
Eindhoven University of Technology, Netherlands†

Traumatic brain injury (TBI) is considered as a widespread problem in case of a road traffic crash situation. Finite Element models are being developed, in order to predict the occurrence of TBI. Current head models contain a somewhat detailed geometrical description of several anatomical components but often lack accurate validated descriptions of the mechanical behaviour of brain tissue. A dedicated nonlinear constitutive model for brain tissue has been developed and the consequences of constitutive nonlinearities are systematically investigated. Furthermore, current head models focus almost entirely on a macroscopic description, thereby ignoring the effect of smaller scale heterogeneities in the brain. A wide range of length scales from several micrometers at the cellular level to several decimeters at the head level are concerned with the development of TBI. In this work, a connection between the different length scales involved in TBI is made.

Microvascular-based multifunctional structural materials

11518
Tue·11:20·2

Scott White,† Nancy Sottos, Jeff Moore, Jennifer Lewis and Ken Christensen
University of Illinois, USA†

Vascular architectures with defined circulatory pathways enable new functionalities in structural materials systems. Biological systems provide a rich source of models and inspiration for synthetic systems and two examples are discussed and demonstrated in self-healing and self-cooling. This new material concept for multifunctional systems is described in which a three-dimensional microvascular network of microchannels is embedded and contains a circulating fluid stream. Initial demonstrations of self-healing functionality have verified the underlying concept and current work is extending these principles to self-cooling applications.

Computational simulation of red blood cell motion in microvessels and bifurcations

11593
Tue·11:40·2

Timothy Secomb,† Jared Barber, Jonathan Alberding and Juan Restrepo
University of Arizona, USA†

Motion and deformation of mammalian red blood cells (RBCs) in microvessels are simulated using a two-dimensional computational model. The RBC is represented as a set of interconnected viscoelastic elements suspended in a viscous fluid. The equations of equilibrium and fluid motion are solved using a finite-element method. Computed cell shapes agree well with corresponding experimental observations. The method is used to predict RBC motion in diverging microvascular bifurcations. Relative to the streamlines of the underlying flow, cells move toward the centerline upstream of the bifurcation. When a slowly moving cell close to the flow divider partially enters one branch, increased shear stresses are generated on the side of the cell toward the flow, because flow rate is fixed. This can cause the cell to cross back over the flow streamlines and enter that branch. The results provide a basis for analyzing the unequal partition of RBCs and plasma in diverging bifurcations.

Influence of endothelium monolayer unevenness on leukocyte deformation and migration

11697
Tue·12:00·2

Pushpendra Singh,† Qian Jin, Claude Verdier, Nadine Aubry,
Roxana Chotard-Ghodsnia and Alain Duperray
New Jersey Institute of Technology, USA†

Direct numerical simulation (DNS) and experimental approaches are used to study the migration of a leukocyte in a pressure driven flow inside a rectangular channel as it interacts with a lower wall covered by a modeled endothelial monolayer. The unevenness of the latter is mimicked by a layer of rigid spheres that are arranged periodically and the leukocytes are represented by a composite drop model in which the cytoplasm and nucleus are considered as Newtonian and viscoelastic fluids, respectively. The adhesion force between the leukocyte and the endothelium wall is modeled by an adhesion potential model. The numerical code, based on the finite element method and the level-set technique (to track the cell membrane), is used to study the time dependent deformation and motion of the leukocyte, and how those vary as a function of Reynolds and capillary numbers. Results are found to be in qualitative agreement with experiments.

Recent progress in the theoretical and computational modelling of flow in 3D collapsible tubes

10348
Tue·12:20·2

Matthias Heil† and Jonathan Boyle
University of Manchester, UK†

This talk presents an overview of recent work (much of which was done jointly with Sarah Waters and Robert Whittaker from the University of Oxford, and Oliver Jensen from the University of Nottingham) on the theoretical and computational modelling of flow in the Starling Resistor—an experimental setup widely used to study collapsible tube flows. We present a mechanism that explains the development of self-excited oscillations in a particular parameter regime in which the tube wall performs high-frequency oscillations. We provide theoretical predictions for the flow rate at which self-excited oscillations are likely to develop and contrast these with direct numerical simulations of the system.

An actin-driven model for neuronal growth cone motility and axon guidance

10011
Tue·16:00·2

Zhu Weiping
Shanghai University, China

The model describes the growth cone motility in a discrete 2D structure of filopodia and lamellipodia. It takes into account the force generation, the adhesion to the ECM and the guidance by cues. Protrusive or contractive force is generated by actin polymerization or depolymerization that is expressed as changes of the volume fraction of actin polymer. Adhesion to the ECM is depicted as a stick-slip block combined with a smooth plug, which makes freely spread with conditioned contraction. A continuity equation defines how the polymer volume fraction changes due to its transport velocity, the polymerization and depolymerization, as well as the concentration and gradient of guidance cues. Finally, the growth cone migration is treated as a resultant of movements of every element of the cone structure. The simulation shows the central features of growth cone migration as characterized in terms of experimentally measurable quantities.

The collective behavior of sarcomere ensembles: evolution of non-uniformities and insights on muscle function

10555
Tue·16:20·2

Kaushik Bhattacharya† and Sefi Givli
California Institute of Technology, USA†

Muscles have a hierarchical structure that spans several scales. While individual scales are well understood, much remains unknown regarding the interaction between the scales. Importantly, models of single sarcomere (the basic contractile unit) do not explain various experimental observations on the macro-scale. This paper starts with well-established models of sarcomeres, and rigorously derives the behavior of the myofibril, the basic macroscopic unit made up of thousands of sarcomeres. The key idea ?and departure from prior work ? is to study the evolution of the probability distribution of sarcomere lengths in the presence of stochastic variability and biological variability. The resulting model reproduces experimental results, explains some puzzling observations, and provides new and important insight.

Russian doll poroelasticity; a model for fluid transport in tissues

10572
Tue·16:40·2

Stephen Cowin† and Gaffar Gailani
City College of New York, USA†

A poroelasticity theory for porous materials with nested pore space structures is developed as a model for the interstitial fluid flow in tissues. The theory concerns the poroelasticity of materials with multiple connected porosities with different characteristic sizes and therefore different permeabilities in which the smaller porosity with the smaller permeability must be supplied with fluid and drain its fluid through the larger permeability. This nested poroelasticity theory is applied to the development of understanding of the interstitial flow between the vascular porosity and the lacunar-canalicular porosity in bone tissue and it is also used to explain why the lacunar-canalicular porosity is the strong candidate for the location of the mechano-transduction system in bone tissue.

Three-dimensional computational modeling and simulation of cell motion on adhesive surfaces in shear flow

11035
Tue·17:00·2

Prosenjit Bagchi† and Vijay Pappu
Rutgers University, USA†

3D numerical simulations are presented on rolling motion of cells on adhesive surfaces in shear flow as a model for leukocyte rolling over selectin-coated surfaces. The computational model is based on immersed boundary method for cell deformation, and Monte Carlo simulation for receptor/ligand interaction. Cells are modeled as deformable capsules. Microvilli on the cell surface are modeled as viscoelastic strings. The multiscale model is shown to predict the characteristic 'stop-and-go' motion of rolling leukocytes. Effect of cell deformation and microvilli distribution on rolling characteristics is studied. Adhesion is seen to occur via multiple microvilli, each of which forms multiple bonds. The adhesion force is concentrated in only rear-most part of a cell. It is also shown that only the microvilli whose undeformed length is above a cut-off length, participate in bond formation. The cut-off length increases with increasing cell rigidity.

Non-Newtonian fluid flow simulation in a progressively enlarged aneurysm model

11470
Tue·17:20·2

Panagiotis Neofytou,† Sokrates Tsangaris and Michalis Kyriakidis
National Technical University of Athens, Greece†

The study is focused on the numerical investigation of the flow field induced by the unsteady flow in the vicinity of an abdominal aortic aneurysm model. The Computational Fluid Dynamics code used is based on the finite volume method whereas for modelling the rheological behaviour of blood, the Quemada non-Newtonian model is employed, which is suitable for simulating the two-phase character of blood. For examining its non-Newtonian effects a comparison with a corresponding Newtonian flow is carried out. Furthermore, the investigation is focused on the distribution of the flow-induced forces on the interior wall of the aneurysm and in order to study the development of the distribution with the gradual enlargement of the aneurysm, three different degrees of aneurysm-growth have been assumed. Finally and for examining the effect of the distribution on the aneurysm growth, a comparison is made between the pressure and wall shear-stress distributions at the wall for each growth-degree.

Separatrices and basins of stability from time series data **11127** Wed·10:40·2

Shane Ross† and Martin Tanaka
Virginia Tech, USA†

An approach is presented for identifying separatrices in state space generated from noisy time series data sets representative of those generated from experiments. We demonstrate how Lagrangian coherent structures (LCS), ridges in the state space distribution of finite-time Lyapunov exponents, can be used to locate these separatrices. As opposed to previous approaches which required an entire vector field at each instance in time, this method can be performed using a single trajectory that evolves over time. The method is applied to a biomechanics simulation in which the separatrix reveals a basin of stability. The results of the nonlinear analysis show that the LCS calculated from only trajectory data aligns well with the LCS found using the traditional vector field analysis methods. In general, we believe this method provides a fruitful approach for extracting information from noisy experimental data regarding boundaries between qualitatively different kinds of motion.

Computational design of novel stem cell based therapies for myocardial infarction **11345** Wed·11:00·2

Ellen Kuhl,† Christopher Zarins, Oscar Abilez, Joe Ulerich and Serdar Goktepe
Stanford University, USA†

This contribution focuses on the computational design of novel stem cell based therapies to treat cardiovascular diseases such as myocardial infarction. The underlying theoretical framework is based on the kinematics of finite growth in combination with open system thermodynamics. The computational simulation is embedded in a nonlinear finite element approach in which tissue growth in response to pressure overload is characterized through a single scalar-valued internal variable driven by the volumetric stress. The long-term response to myocardial infarction is elaborated in terms of a generic biventricular heart model. We present a first attempt to compare two competing novel therapies to restore cardiac function: cell injection into the myocardium and transplantation of tissue engineered cardiovascular grafts. The quality of both therapies is characterized in terms of the ejection fraction that is defined as the stroke volume scaled by the end-systolic volume.

Material characterization of biological membranes by inverse analysis **11386** Wed·11:20·2

Martin Kroon† and Gerhard Holzapfel
Royal Institute of Technology, Sweden†

An inverse method for material characterization of biological membranes is proposed. The constitutive model includes four material parameters, whose distributions are to be estimated. The estimation method consists of the following major steps: (a) performing experiments on the membrane whose properties are to be determined, (b) defining a corresponding finite element (FE) model, and (c) minimizing an error function with respect to the material parameters. In a numerical example, we assess the proposed method by trying to reestablish a known reference distribution of material properties in a (reference) membrane. The standard deviation of the estimated material parameters (as compared to the reference field) was within just a few percent.

Cosserat theoretical modeling of single actin filament as a twisted elastic filament

11424
Wed·11:40·2

Hidetaka Yamaoka† and Taiji Adachi
RIKEN, Japan†

Mechanically interesting twisted filaments are found in important substances in living cells, such as DNA and cytoskeletal actin filaments. In particular, the actin filament forming bundling/branching structure exhibits buckling behavior and tensile-torsional coupling behavior. These structural changes and mechanical behavior are closely related to its microstructure, while Cosserat continuum theory is suitable for describing dynamics of continua with microstructures. Here, we consider a single twisted filament as a three-dimensional elastic filament, and describe its mechanical behavior based on Cosserat theory. Then we derive equations of motion for the actin filament by the variational principle, and investigate assumptions on which the equations of motion are reduced to certain simple ones. As a result, we find that the tensile-torsional coupling behavior of the actin filament occurs when each point of its axial curve does not correspond to the center-of-mass of each cross-section.

Ionised media and fractures: application to cartilaginous tissues and oil industry

11951
Wed·12:00·2

Jacques Huyghe,† Rene de Borst, Joris Remmers and Famke Kraaijeveld
Eindhoven University of Technology, Netherlands†

Ionized media are ubiquitous in nature. Our body holds onto water through ionized macromolecules that bind water up to a 1000 times their own mass. Clays and shales do a similar trick in the geoworld. Localization of deformation and fractures are very common. Bore hole instability through fracture of swelling shales accounts for more than a billion dollar damage to the oil industry each year. Herniation of the intervertebral disc is a even more devastation problem in health. Our group approaches localization through both experiments, numerical modeling and analytical modeling. Propagation of mode I and mode II cracks through ionized media is done by means of Partition of Unity. The crack is a discontinuity of both the displacement as the chemical potential field. The results are validated by means of an analytical solution of dislocation in a swelling medium. Experimental verification requires confocal and two photon microscopy.

An anisotropic micro-sphere-based model for arterial tissue

12078
Wed·12:20·2

Andreas Menzel,† Manuel Doblare, Miguel Martinez and Victor Alastrue
Technical University of Dortmund, Germany†

A micro-structurally based model for soft anisotropic biological tissue modelling is here presented. Macroscopic fibre contributions are thereby based on the sum of contributions of micro-fibre-families. Their contribution to the overall constitutive relations is calculated by means of numerical integration over the surface of the underlying micro-sphere. The simulation results obtained, based on an identification of the material parameters for arterial tissue and the incorporation of residual stresses, confirm the soundness and applicability of the proposed formulation to model fibre-reinforced soft biological tissues.

Modeling skin wrinkling for reconstructive surgery: the effects of natural tension

11305
Wed·12:40·2

Luigi Gambarotta,† Andrea Cavicchi and Roberta Massabò
University of Genova, Italy†

A model is presented for the simulation of procedures of reconstructive surgery characterized by the excision of a cutaneous defect and the closure and suture of the wound edges. The skin is modeled as a plane membrane undergoing large deformations having a Fung type constitutive response. Skin wrinkling, which is a typical outcome of the surgery in the form of extrusion of the wound edges and dog-ears, is accounted for through a modification of the elastic potential as proposed by Pipkin's Relaxed Energy Density theory. The post buckling analysis of a stretched annular membrane performed by Geminard *et al.* (2004) is used to validate the model under conditions similar to those of the surgery and to highlight the influence of a pre-existing tension in the membrane on the extension of the wrinkled regions. The model is applied to simulate different surgical procedures and investigate the effects of the natural tension in the skin and the shape and size of the excisions.

Liquid crystal model of vesicles under electromechanical fields

10933
Thu·09:15·2

Xi-Qiao Feng,† Ling-Tian Gao and Huajian Gao
Tsinghua University, China†

An electromechanical liquid crystal theory is developed for modeling the morphology evolution of a lipid vesicle under mechanical and electrical fields. Firstly, a general equation that governs the vesicle shape is established by considering the effects of elastic bending, osmotic pressure, surface tension, Maxwell pressure, as well as the flexoelectricity and dielectricity of the vesicle. The shape equations are analytically solved for axisymmetric vesicles. Furthermore, a phase field model is proposed to solve the highly nonlinear electromechanical equations. The effects of mechanical-electrical coupling on the morphology evolution of vesicles under a steady electric field are analyzed via some examples. Our theoretical predictions have a good agreement with relevant experiments. This study provides a promising tool to investigate the deformation of vesicles under coupled electromechanical fields and to understand various electrophysiology phenomena of cells (e.g., electroporation).

The hysteretic large strain behavior of mussel byssal threads

11672
Thu·09:35·2

Brian Greviskes
Massachusetts Institute of Technology, USA

This study investigates byssal threads, the attachment appendage of mussels, which withstand remarkably resilient yet dissipative stretches. These threads consist of two axial regions proximal and distal to the mussel stem. Monotonic and cyclic tensile tests at varying strain rates find the proximal region to exhibit a more compliant behavior when compared to the distal region. Both regions show increasing compliance with stretch which is evident during cyclic loading. The behavior is linked to the copolymeric microstructure, which consists of filament bundles with molecular folded domains. As the thread is stretched these domains unfold, increasing the tension-free length of the filaments. Upon unloading the domains refold in a time dependent fashion. A model for the stress-strain behavior of the threads, based upon the unfolding, is developed. The model captures the rate-dependence of the material and the overall behavior in loading, unloading, and reloading.

Red blood cell deformation behavior in a high-shear flow

12181
Thu·09:55·2

Shigeo Wada,† Masanori Nakamura and Sadao Bessho
Osaka University, Japan†

Deformation behavior of a red blood cell (RBC) in a high-shear flow was investigated. The RBC was modeled as a closed shell membrane consisting of spring networks which resist stretching and bending. Given a flow field, deformation and motion of RBC were determined toward the minimum energy state. The simulation of RBC in a parallel shear flow showed elastic parameters of RBC such as tank-treading frequency and deformation index were well agreed with experimental results both qualitatively and quantitatively. The simulation of RBC behavior in a back-step flow demonstrated that the shape was determined not only by instantaneous fluid force acting on it but also its deformation history. There was no consistent tendency between the maximum of the first principal strain and conventionally used hemolysis index. These results addressed the necessity to consider dynamic deformation of individual RBCs including their flow trace and deformation history for better evaluation of hemolysis.

Peristalsis and hydrodynamic instabilities

11063
Thu·10:15·2

Jerome Hoepffner† and Koji Fukagata
KEIO University, Japan†

Peristaltic pumping is considered in view of early nonlinear mechanisms in hydrodynamic instabilities. A propagating wall deformation generates pressure gradients in the flow, which act together with viscous friction to induce a mean flux. This process is analyzed in a plane channel, and a model is derived which agrees well with computed flow solutions. For the considered wall deformation, the pumping effect is found independent of the Reynolds number. Implications for instability in flows bounded by compliant walls are discussed.

Elementary mechanics of muscular exercise

10302
Thu·14:00·11

Antonio DiCarlo
Università Roma Tre, Italy

Go to the gym, pick up a dumbbell, raise your forearm at ninety degrees with your upper arm, and hold on. Whoever has tried knows that an isometric exercise can be strenuous. So, you may be doing a hard workout, yet null work is being done: no motion, no power expended. What's wrong? In actual fact, zillions of minuscule myosin heads keep on moving inside your biceps while your arm stays still. A decent model of muscular exercise, while eschewing all molecular details, should account for their net results on the gym scale. Here I present the simplest model of this kind, based on a macroscopic caricature of actin-myosin sliding and myosin action, treated as independent mechanisms. Avoiding to lump them into a single effective mechanism is of the essence whenever keeping track of the power expended separately by each of them is crucial. In fact, the effort demanded by an isometric exercise and the energy apportionment required are simply cancelled in the lumping.

Simulation of migrating cell growth under limited nutrient supply based on a cellular automata model

10940
Thu·14:05·11

Chih-Ang Chung† and Chih-Di Chen
National Central University, Taiwan†

A discrete cellular automata model combined with a differential oxygen diffusion reaction equation is adopted to simulate the development of cellular scaffolds for tissue engineering applications. The local oxygen concentration influences the local cell viability such as the cell growth and motility. On the other hand, cells consume oxygen to maintain metabolism and perform proliferation, which affect the oxygen concentration in return in a coupled manner. The cellular automata algorithm is used to investigate how cellular scale behaviors such as division, random walks and contact inhibition ultimately affect the cell population in the scaffold. Oxygen up taken by the cells and diffused into the scaffold from the scaffold periphery is modeled by a partial differential equation and solved by a finite difference method. A two-dimensional simulation is then carried out for the static culture condition. The temporary evolution of cells population and oxygen concentration are presented.

Micro and macro shape deviations of the contact areas of the hip joint endoprosthesis

11297
Thu·14:10·11

Vladimir Fuis,† Martin Houfek and Premysl Janicek
Brno University of Technology, Czech Republic†

The paper deals with the problems of ceramic head of hip joint endoprosthesis destructions, and with assessing the impact of shape deflections of conical surfaces on the tensile stress in the head. Concerned are shape deviations from the ideal conical surfaces of the stem and the head of the endoprosthesis. The shape deviations may be modelled at the macro-level—this concerns model shape inaccuracies such as deviation from the nominal degree of taper, ovality, and their combination, or, possibly, at the micro-level—when the stochastic distribution of unevenness on the contact areas is respected. The problem of stress in ceramic heads was solved using the algorithm of the finite element method system ANSYS under ISO 7206-5 loading. In the paper are presented and analysed the results of solution of the macro-level shape deviations and micro-level shape deviations, obtained from measurements made on the cones of stems and heads.

Structure overload and structural anisotropy in human vertebral trabecular bone

11317
Thu·14:15·11

Nicola Fazzalari,† Arash Badiei and Murk Bottema
The University of Adelaide, Australia†

This study investigates the mechanical relationship of longitudinal and transverse elements of vertebral trabecular bone to determine the contribution of structural anisotropy in explaining the variance in trabecular bone mechanical integrity. Vertebral bone cubes were imaged using microcomputed tomography then tested in orthogonal directions (superoinferior [SI] vs anteroposterior [AP]) on a universal mechanical testing machine to 10% apparent strain by uni-axial compression. The apparent ultimate failure stresses (UFS), elastic modulus (E) and toughness modulus (u) for both first and second overloads were significantly greater in SI than AP. Even after overload in the orthogonal direction, UFS, E and u were significantly greater in SI than AP direction. Univariate and multivariate analyses indicate that bone volume fraction is an essential determinant of trabecular bone mechanical integrity and trabecular bone structural anisotropy makes a conditional contribution.

Study on deformation of vesicle membrane based on evolution of topological defects

11450
Thu·14:20·11

Akihiro Nakatani† and Yasuyuki Shobatake
Osaka University, Japan†

Quasi-statical shape changes of vesicle membranes in various surface area conditions from a viewpoint of minimizing the elastic bending energy is studied by using a phase-field method. The fluid - vesicle interaction is also studied. Global topological changes of shape with a drastic change in energy, hysteresis behavior and deformation due to the pressure have been observed. In order to extend these theory, the relationship between the change of intrinsic geometry of membrane and the nucleation and annihilation of topological defects is discussed. A criterion of yield condition is introduced as the non-conservative change of topological defects. Some problems by using a stripe model are examined.

Investigation of the surface interactions of the implant-bone

11454
Thu·14:25·11

Romuald Bedzinski
Wroclaw University of Technology, Poland

A thesis was advanced that an appropriate combination of the most significant factors: implant surface and the type of an indirect layer, as well as proper relations of the implant-bone deformations should allow to obtain an optimum solution to the problem of reactions between bone and an implant. The primary goal of the work is to develop a technology of obtaining protective coatings for medical implants by a sol-gel method. Physicochemical, mechanical and biological properties of derived thin films have been measured. Basing on the fatigue strength test, tensile tests and SEM microscopy it could be concluded that a high level of adhesion characterized examined coatings. The cultured cells proliferated on the surface which allows us to assume that these sol-gel coatings are a good base for the cells to adhere.

An elastica approximate for fibers and fibrous networks

11500
Thu·14:30·11

Carlos Castro,† Matthew Lang and Mary Boyce
Massachusetts Institute of Technology, USA†

Wavy fibers found in biological and synthetic material systems exhibit a highly nonlinear force-extension behavior due to the straightening out of the waves. Here, an analytical model for the force-extension behavior of wavy fibers is developed based on the Euler elastica solution for unbending curved beams. Expressions are derived to describe the fiber mechanical response in the limit of small extensions and in the limit of large forces. A logical weighted combination of these expressions is applied to describe the complete unbending of the fibers of interest, and direct axial fiber stretching is incorporated to capture extensions beyond the fiber contour length. Additionally, the model is fit to experimental stress-strain data for a rat tail tendon collagen fascicle. A fascicle wavelength of 114 microns and an elastic modulus of 384 MPa were identified. Finally, we incorporate the model into a 2D network of fibers to describe membrane stress-strain behavior.

An inverse dynamic model of an arm via Kane's method: torque determination in smash activity

11633
Thu·14:35·11

Azmin Rambely[†] and Fadiah Ariff
Universiti Kebangsaan Malaysia, Malaysia[†]

A 2D model for three link kinematic chain of an arm is developed using Kane's method. The model represents an arm with three joints, namely shoulder, elbow and wrist joints, which comprises of upper arm, lower arm and hand- racket segments. The model is developed to determine the torques of each segment by obtaining the inverse dynamic matrix through the development of kinematic equations and dynamics equation using Kane's method. The inverse model obtained showed that torque at the elbow joint produced the highest value compare to that of the other joints (shoulder and wrist) during the badminton smash activity.

Forces on an adhering cell

11690
Thu·14:40·11

Joseph Berry,[†] Mark Thompson, Josie Carberry and Shaun Jackson
Monash University, Australia[†]

A basic 2D numerical model has been developed to gain insight into the surface deformations and forces experienced by an adhering, elastic blood cell in flows with negligible inertial effects. The deformation of an initially circular cell is considered, in both uniform unbounded flow and bounded linear shear flow. When adhering in unbounded uniform flow, the cell experiences a drag force that increases non-linearly with dimensionless velocity. When adhered to a plane wall in linear shear flow, the cell experiences a drag force that increases linearly, and a lift force that increases non-linearly, with dimensionless shear rate.

Friction drag and pressure drag acting on an angled-wavy plate

11760
Thu·14:45·11

Naoki Yoshitake,[†] Yoshimichi Hagiwara, Hui Zhang and Yoshihiko Ozaki
Kyoto Institute of Technology, Japan[†]

We have conducted experiments of turbulent water flow over an angled wavy plate on the bottom of an open channel. This plate consists of a thin silicon-rubber sheet and a metal base. The plate is a model of the folded skin of a swimming dolphin. The local time-averaged wall-shear stress is calculated from the local mean velocity, which is measured with a PTV technique. The total drag is estimated from the measured strains of two cantilevers, which support the plate. The results show a certain reduction of the friction drag. This is due to the separation bubbles located above the downhill of the wavy plate. The pressure drag, which is estimated from the difference between the total drag and the friction drag, increases due to the ridges of the angled wavy plate. However, the increasing rate of the pressure drag is lower than that estimated for a non-angled wavy wall. This may be due to the instability of the separation bubbles caused by weak secondary flow along the ridges.

FSM03 :: Chaos and pattern formation in fluid and solid mechanics

Chairs: Tomasz Kapitaniak (Poland) and Edwin Kreuzer (Germany)

Wed	10:40–13:00	Room 4	Lectures
Thu	14:40–14:55	Room 8	Seminars

Misleading dye visualization near a 3D stagnation point with applications to the vortex breakdown bubble

10238
Wed·10:40·4

Morten Brons,† Kerry Hourigan and Mark Thompson
Technical University of Denmark, Denmark†

An analytical model is constructed of the dye visualization expected near a three-dimensional stagnation point in a swirling fluid flow. The model predicts dye traces that oscillate in density and position in the meridional plane in which swirling flows are typically visualized. Predictions from the model for steady vortex breakdown bubble are compared with numerical predictions and experiments. Even for a perfectly axisymmetric flow and breakdown bubble, the combined effect of dye diffusion and the inevitable small errors in the dye injection position lead to the false perception of an open bubble structure with folds near the lower stagnation point. The numerical flow structures can be remarkably similar to those observed in flow observations and computational predictions with geometric asymmetries of the rig. Thus, when interpreting dye visualization patterns in steady flow, it is important to take into account the relative diffusivity of the dye and the accuracy of its injection.

Chaos thresholds in vibro-impact systems with heavy elastic elements

10574
Wed·11:00·4

Tomasz Kapitaniak,† Barbara Blazejczyk-Okolewska and Krzysztof Czolczynski
Technical University of Lodz, Poland†

A vibro-impact system is usually modeled as a spring-mass system with amplitude constraint and as impacts give rise to discontinuity it can exhibit complex dynamical behavior. Recently such a systems has become an object of intensive studies resulting in many new theoretical results. In most of these studies it has been assumed that the elastic elements are massless. We propose the model of vibro-impact system with heavy elastic elements and develop an approximate analytical method of determination of the thresholds of its chaotic behaviour. Stable periodic responses that describe regular motion with impacts of the mechanical system exist in considerably wide ranges of parameters describing this system.We discuss the importance of the consideration of the mass of the elastic elements pointing out what kind of dynamical phenomena are not visible in the simplified model. This analysis will be helpful in modeling systems with impacts of non-negligibly high mass of elastic elements.

Experimental chaos in impact oscillator

11118
Wed·11:20·4

Ekaterina Pavlovskaia,† Marian Wiercigroch, James Ing and Soumitro Banerjee
Aberdeen University, UK†

Nonlinear dynamics of an impact oscillator with a one sided elastic constraint is studied experimentally and the results are compared with the predictions obtained using its mathematical model. A particular attention is paid to the chaos recorded near grazing frequency when a non-impacting orbit becomes impacting one under increasing excitation frequency. Extensive experimental investigations have been undertaken on the rig developed at the Aberdeen University. Different bifurcation scenarios under varying excitation frequency near grazing were recorded for a number of values of the excitation amplitude. The mass acceleration signal was used to effectively detect contacts with the secondary spring. It was found, that the evolution of the attractor is governed by a complex interplay between smooth and non-smooth bifurcations. In some cases the occurrence of coexisting attractors is manifested through a discontinuous transition from one orbit to another through boundary crisis.

Chaos control by application of magnetorheological damping

11154
Wed·11:40·4

Jerzy Warminski† and Krzysztof Kecik
Lublin University of Technology, Poland†

The paper deals with theoretical and experimental analysis of chaos control of an autoparametric system with a pendulum by using a magnethoreological (MR) damper. The investigations are curried out close to the main parametric resonance in the neighbourhood of the instability region which can appear inside the resonance. It is shown numerically and experimentally that MR damping can effectively reduce chaotic oscillations without a lost of the dynamical vibration absorption.

Nonsmooth mechanics: challenges and unsolved problems

11202
Wed·12:00·4

John Hogan
University of Bristol, UK

A mechanical system is nonsmooth if there are abrupt changes in position or velocity or where a threshold (or boundary) exists. Examples include the impact oscillator, gear systems and the friction oscillator. These systems have unique dynamics such as grazing, period adding bifurcations, Zenoness, robust chaos and big bang bifurcations. This paper contains a review of recent work in this field and highlights the significant number of open problems that need to be addressed before these systems can be properly understood.

Coexistence of synchronous states in chaotically driven mechanical oscillators

11563
Wed·12:20·4

Andrzej Stefanski† and Przemyslaw Perlikowski
Technical University of Lodz, Poland†

In this paper a coexistence of the complete, phase and generalized synchronization of the mechanical oscillators driven by the chaotic signal is demonstrated. We identified the close dependence between the changes in the spectrum of Lyapunov exponents and a transition to different types of synchronization. The strict connection between the complete synchronization (or imperfect complete synchronization) of response oscillators and their phase or generalized synchronization with the driving system is shown. We argue that the observed phenomena are generic in the parameter space and preserved in the presence of a small parameter mismatch.

Exploring extensive chaos in Rayleigh–Bénard convection using fractal and Karhunen-Loève dimensions

11635
Wed·12:40·4

Andrew Duggleby† and Mark Paul
Texas A&M University, USA†

Using large-scale numerical simulations we quantitatively explore extensive spatiotemporal chaos in a fluid layer heated from below (Rayleigh-Bénard convection). We study a cylindrical convection layer containing a Boussinesq fluid at constant Rayleigh number with no-slip boundaries and perfectly conducting lateral sidewalls for parameters that yield spiral defect chaos. The increasing disorder that results as the system size is increased is explored using Lyapunov-exponent based diagnostics and a Karhunen-Loève decomposition. Both the fractal and the Karhunen-Loève dimension are found to scale linearly with system size over the same range of finite-sized geometries. The Karhunen-Loève dimension is over fourteen times as large as the fractal dimension and even for small sized systems requires hundreds of modes to describe the dynamics. These results are used to shed further insight into the spatiotemporal dynamics that comprise extensive chaos.

Acoustic chaos in sonic infrared imaging

10856
Thu·14:40·8

Golam Newaz,† Robert Thomas, Lawrence Favro and Xiaoyan Han
Wayne State University, USA†

Frictional heating generated by low-frequency ultrasound makes cracks in solids visible to IR cameras. Chaotic effects, including the appearance of fractional frequencies result from the non-linear interaction between the ultrasonic source and the sample. These unexpected frequencies are the major source of crack heating in Sonic IR imaging. Enhanced crack heating results from the dense acoustic spectrum produced by 'infra-harmonics' and their corresponding harmonics. The transducer-sample interaction has been modeled using a vibrating mass bouncing against a rigid wall with a constant applied force. In this analytic model, the mass vibrates sinusoidally with a fixed frequency. This model produces the characteristic infra-harmonic behavior, with frequent switching of the fractional infra-harmonic denominator during short intervals of pure chaos. Dynamic finite element models have confirmed the analytic results, and both are in good agreement with experimental results.

Normal forms of Hamiltonian systems via curvature line transformations

11031
Thu·14:45·8

Xinhua Zhang
Xi'an Jiaotong University, China

A new intrinsic connection between the normal forms of Hamiltonian dynamical systems and the geometric transformations induced by the curvature lines of the corresponding Hamiltonian function is proposed. For an N-DOF Hamiltonian dynamical system, the Hamiltonian function can be viewed as a $2N$-hypersurface in $(2N + 1)$ dimensional space with the phase space as its underlying space. There are $2N$ curvature lines of the hypersurface passing through the origin. Projecting the curvature lines to the underlying space, one obtains a new curved coordinate system. Transformation of the original coordinate system to the new curved one will naturally reduce the original Hamiltonian dynamical system to its normal form. Due to the complexity of the curvature line equations, one can only get series solutions of such curvature line equations. The Taylor series solutions of the curvature lines with various truncated orders will lead to the normal forms of the Hamiltonian systems with the same orders.

Bifurcation and chaos in drive systems

11488
Thu·14:50·8

Martin Houfek,[†] Vladimir Fuis and Ctirad Kratochvil
Brno University of Technology, Czech Republic[†]

Stability analysis can not be omitted when examining the dynamic properties of drive systems. In case of nonlinear systems and its models one can also expect occurrence of chaotic movements. The approach towards the analysis of its occurrence possibilities will be different when analyzing models with one or a few degrees of freedom or models of real technical systems. Those problems are addressed in the contribution. We can do a set of computational simulation with this system. The aim of this simulation is to recognize a possibility of occurrence of chaotic behaviour or to find a bifurcation states as we describe it in paper. The Matlab–Simulink system was selected for simulation, because implementation of the equations is quite simple and algorithms for simulation of dynamic systems in Matlab are robust and sophisticated. Good and long experience with this simulation system is another reason for selection of this system.

FSM04 :: Fluid–structure interactions

Chairs: John Grue (Norway) and Michael Paidoussis (Canada)

Mon	16:25–17:45	Room 8	Lectures
Thu	14:00–15:10	Room 10	Seminars
Fri	09:15–10:35	Room 10	Lectures
Fri	11:00–12:20	Room 1	Lectures

Flow around a tethered neutrally-buoyant sphere

10871
Mon·16:25·8

Kerry Hourigan,† Hyeok Lee and Mark Thompson
Monash University, Australia†

The sphere is the generic geometry for three-dimensional bluff body flows. The tethering of a bluff body in a flow is one of the simplest means of allowing vortex induced vibration. In the fixed body case, buoyancy is not a factor. Here, the flow induced vibrations of a tethered sphere is investigated for the special case of neutral buoyancy, providing a bridging comparison with the fixed sphere case. A high order spectral element method is employed to predict the wake structures and oscillations of a sphere over a range of Reynolds numbers. The predicted transitions in the wake are related to those observed for the fixed sphere case. Six different transition regimes are found, corresponding to different states of the wake and body oscillation. Experimental validation and the effect of slight buoyancy will also be presented at the conference.

Energy transfer in fluid–structure interactions

10968
Mon·16:45·8

Tatyana Krasnopolskaya,† Eugene Nikiforovich and Aleksandr Shvets
Institute of Hydromechanics, NASU, Ukraine†

Fluid free surface oscillations in a cylindrical tank under interaction with an excitation machine of a limited power-supply (so-called “limited excitation” phenomena) are investigated in detail. For a complex system—a tank with fluid and an excitation machine—the regions of parameters for four steady-state regimes: stationary, periodic, almost-periodic and chaotic are determined. Attention is concentrated mainly on the properties of chaotic attractors (namely, on a new type of intermittency) and energy transfer between subsystems. Because the total power for every regime is balanced by the rate of change of the total energy of the whole system it is demonstrated how different the energy distribution between subsystems for every of steady-state regimes is and how changes of the damping force coefficient may control the chaotic regimes.

Collective flutter of a parallel plate assembly

10084
Mon·17:05·8

Lionel Schouveiler,† Christophe Eloy and Marcelo Abarca
Université Paul Cezanne, France†

Flutter of an assembly of parallel flexible plates in a uniform flow is experimentally and analytically investigated. The linear stability is analyzed considering a system of n infinite plates in a potential flow. Coupled flutter modes are deduced with their dispersion relation. Experiments performed with two plates are also presented. In-phase and out-of-phase flutter are observed. Flutter modes, flutter frequencies and critical velocities are in agreement, at least qualitative, with theoretical predictions. Experiments with more plates are currently in progress.

Flow behind a cylinder forced by a combination of oscillatory translational and rotational motions

10684
Mon·17:25·8

David Jacono,† Mehdi Nazarinia, Mark Thompson and John Sheridan
Monash University, Australia†

This paper presents experimental results for flow behind a cylinder undergoing forced motion. The motion consists of two independent oscillations: cross-stream translation and rotation. Previous studies have extensively investigated the effect of these motions individually on cylinder wakes; however, the investigation of their combined effect is new. The motivation for studying such a flow lies in its application to vortex-induced vibration (VIV), and its suppression, and biomimetic motion. The results presented here focus only on the effect of the phase difference between the two motions. The results show that there is an unexpected loss of lock-on between the vortex shedding and the translational motion for a finite range of phase differences.

Hydroelastic analysis of multiple articulated floating elastic plates

10186
Thu·14:00·10

Trilochan Sahoo,† Joydip Bhattacharjee and Debabrata Karmakar
Indian Institute of Technology, Kharagpur, India†

In the present paper, the surface gravity wave scattering by multiple articulated floating elastic plates of finite length is analyzed under the assumption of linearized water wave theory in finite water depth. By direct application of the recently developed expansion formulae and associated orthogonal mode-coupling relation for wave structure interaction problems, the boundary value problem is simplified to a linear system of equations. Further, the computational results are derived in an alternate manner using the method of wide spacing approximation. Effect of the stiffness of the connectors on the floating elastic plate is investigated by analyzing the reflection and transmission coefficients.

The effect of surface condition on the vortex-induced vibration response of cylindrical offshore structures

10231
Thu·14:05·10

Brad Stappenbelt
University of Western Australia, Australia

Deterioration of the surface condition of an offshore structure subject to marine fouling may be quantified by its surface roughness. The present study experimentally investigated the influence of the surface roughness on the vortex-induced vibration amplitude response and dynamic drag experienced by linear elastically mounted rigid cylindrical structures. All experimentation was performed under steady uniform current conditions in the stable sub-critical flow regime. The vortex-induced vibration amplitudes and dynamic drag experienced were found to decrease non-linearly with increasing surface roughness. The dynamic drag prediction based on vibration amplitude was also found to be less severe with increasing surface roughness. Offshore structure design based upon the smooth cylinder vortex-induced vibration case would therefore appear to be conservative with regard to dynamic drag force and fatigue load prediction.

10409
Thu·14:10·10

Global chaotic attitude dynamics of completely liquid-filled flexible spacecraft

Baozeng Yue
Beijng Institute of Technology, China

The chaotic attitude dynamics of completely liquid-filled spacecraft going from minor axis to major axis spin under the influence of viscous damping and a small flexible appendage constrained to undergo only torsional vibration is investigated. The equations of motion are derived and then transformed into a form suitable for the application of Melnikov's method. Melnikov's integral is used to predict the transversal intersections of the stable and unstable manifolds for the perturbed system. An analytical criterion for chaotic motion is derived in terms of the system parameters. In addition, the Melnikov criterion is compared with numerical simulations of the system. The dependence of the onset of chaos on quantities such as body shape, inertial momentum of fuel slug, and magnitude of damping values and frequency of flexible appendage vibration are investigated.

10450
Thu·14:15·10

Blast propagation in domains of changing topology

Leonid Antanovskii
Defence Science and Technology Organisation, Australia

This paper addresses the dynamics of shock waves in domains of changing topology, e.g. blast propagation in rooms or passageways of buildings including the effects of the breakage of internal walls or opening structures. A simple model is proposed based on the assumption that the internal structures are thin compared to the characteristic length scale. The numerical model employs a variation of the Godunov scheme coupled with governing equations for the accumulated damage of elements constituting a structural feature, with coefficients depending on material properties and the state of gas in adjacent control cells. When the accumulated damage exceeds some threshold value, the structural element is forced to fail. Numerical simulations demonstrate that the model behaves reasonably well and is capable of providing rough estimates of progressive failure and blast transfer within and between compartmented structures and hence provides useful input to vulnerability assessment codes.

10836
Thu·14:20·10

Evaluation of added mass coefficients of a hull form using Landweber

Hem Wadhwa[†] and Krish Thiagarajan
University of Western Australia, Australia[†]

The 6×6 added mass matrix is one of the important parameters needed to model ship motions in a seaway. The Bieberbach method of conformal mapping, modified by Professor L. Landweber, is used for mapping the exterior of the closed curve i.e. the two-dimensional ship cross-section and its mirror image into the exterior of the circle, oscillating horizontally at a free surface, to calculate the sectional added mass coefficients. The technique is found to be attractive in terms of its mathematical explicitness and computational simplicity. The added mass coefficients of a three dimensional structure can be estimated from its two-dimensional section coefficients at different drafts by incorporating a strip theory approximation. In this paper we have applied this method to evaluate the sway and yaw added mass coefficients, and compared the results with industry-standard boundary element method software, AQWA.

Improvement of aircraft rolling performance using piezoelectric actuators **10947** Thu·14:25·10

Min Li,† Weimin Chen and Ming-Chun Wang
Beijing University of Aeronautics and Astronautics, China†

Air vehicles are optimized for specific flight conditions. Changing the shape of an airfoil to enhance overall aircraft performance has always been a goal of aircraft designers. Recent researches show that using smart material to reshape the wing can improve aerodynamic performance. By distributing piezoelectric actuators on the top and bottom surfaces of a wing, a scheme of fictitious control surface to improve rolling performance for a model based on a high altitude long endurance unmanned vehicle wing is investigated. The effective location of actuators and the effect of aeroelastic deformation on control efficiency are analyzed. Our results demonstrate that for the wing with fictitious control surface, compared with the traditional wing with control surface, the aeroelastic effect would become into a favorable effect and the air performance of flight vehicle would be significantly improved by actively deforming a more flexible wing, and moreover small control energy is needed.

Vortex-induced vibrations of a tethered sphere with neutral buoyancy **11299** Thu·14:30·10

Hyeok Lee,† Kerry Hourigan and Mark Thompson
Monash University, Australia†

The previous study of the same authors numerically identified that there exist six different flow regimes within the range of the Reynolds number $Re = [50, 800]$, which is based on the mean flow velocity (U) and sphere diameter (D), in the case of a tethered sphere with neutral buoyancy. A series of experiments are carried out in a water channel to verify and support the numerical findings in the range of the Reynolds number $= [700, 4000]$ which is higher than those of the numerical study. The position of the sphere is recorded during the experiments. Within the Reynolds range $= [700, 800]$, which covers simulations and experiments, and corresponds to the Regime VI, it is observed that the response of the sphere is irregular. This verify the existence of Regime VI which has been found in the numerical study. It is also observed that the sphere shows quasi-circular motion in the plane normal to incoming flow as the Reynolds number is increased further.

Nonlinear vibration of a curved pipe conveying fluid subjected to tip harmonic excitation tangential to the pipe center line **11348** Thu·14:35·10

Ni Qiao† and Zhang Zilong
Huazhong University of Science and Technology, China†

This paper investigates the forced vibration of a constrained curved pipe conveying fluid subjected to tip harmonic excitation tangential to the pipe center line. The analytical model, after discretization via Differential Quadrature Method (DQM), exhibited extremely rich dynamics. Calculations of bifurcation diagrams, phase-plane portraits and Poincaré maps of the oscillations clearly establish the periodic, chaotic and quasi-periodic motions. It is found that the effect of external excitation and its direction on the vibration of curved pipe is significant. These studies are expected to be useful in further developments to analyze the forced vibration of curved pipes conveying fluid.

DQM for solving stability of a tubular cantilever conveying fluid downwards immersed in a cylindrical container

11356
Thu·14:40·10

Qian Qin† and Wang Lin
Huazhong University of Science and Technology, China†

The vibration and stability of a tubular cantilever conveying fluid downwards and immersed in a cylindrical container are investigated by using the Differential Quadrature Method (DQM). The hanging tubular beam, with fluid flowing inside the cantilever, exiting from the free end, being deflected at the bottom of the container, and thereafter flowing upwards in the annular space between the cantilever and container, is centrally located in a cylindrical container. Based on the DQM, emphasis is placed on the evolution of the eigenfrequencies for the tubular beam with increasing dimensionless flow velocity. The critical flow velocity at which flutter may occur is also obtained. Compared with the conventional Galerkin method and the hybrid Galerkin–Fourier method, DQM is convenient to deal with the boundary conditions of the fluid-conveying beam and can give acceptable precision in the numerical results.

Hydrodynamic behaviour characterization of vertical axis water turbine scale model

11376
Thu·14:45·10

Nicolas Dellinger,† Jean-Luc Achard, Didier Imbault and Ali Tourabi
Laboratoire des Ecoulements Géophysiques et Industriels, France†

This paper deals with experimental characterization of space and time loading fluctuation of Vertical Axis Water Turbines (VAWTs), as well as with the study of their performance characteristics. Furthermore, we present the detailed definition of new test equipment, a six-component force measuring device, devoted to hydrodynamic characterisation of VAWT scale models.

Simulation of unsteady hydrodynamic loadings and structural analysis of vertical axis water turbine

11379
Thu·14:50·10

Jeronimo Zanette,† Cécile Münch and Ali Tourabi
Laboratoire Sols, Solides, Structures-Risques, France†

This contribution deals with design of vertical-axis water turbines (VAWTs) and simulation of blades mechanical behaviour subjected to hydrodynamic loadings generated by the turbulent flow around the turbine. The mechanical stress sustained by the blades depends basically on the hydrofoil geometry and the operating conditions of the turbine. During operating, the blades are subjected to cyclic loadings defined by pressure field's variation as function of azimuthal angle, generated by a complex turbulent flow across the turbine. Thus, the design of VAWTs reveals a multidisciplinary and coupled multiphysics problem.

Impact of a spherical shell on a thin layer of the water

11778
Thu·14:55·10

Tatiana Khabakhpasheva
Lavrentyev Institute of Hydrodynamic, Russia

The paper is concerned with axisymmetrical problem of elastic shell impact onto a thin layer of an ideal incompressible liquid. The spherical shell initially touches the liquid free surface at a single point and then penetrates the liquid layer at a constant vertical velocity. The problem is coupled because the liquid flow, the shape of the elastic shell and the geometry of the contact region between the body and the liquid must be determined simultaneously. The 2D-problem of a circular cylindrical shell impact was considered before by the method of matched asymptotic expansions for analyzes of liquid flow. The present study is extension of the previous one for axisymmetrical case. This extension leads us to investigations of liquid flow in a subdomains and a new matching conditions. The structural analysis is based on the normal-mode method. Strain-time histories of the inner surface of the spherical shell are of particular interest.

Dynamics of fluid-conveying pipes: effects of velocity profiles

11821
Thu·15:00·10

Stephanie Enz† and Jon Thomsen
Technical University of Denmark, Denmark†

Varying velocity profiles and internal fluid loads on fluid-conveying pipes are investigated. Different geometric layouts of the fluid domain and inflow velocity profiles are considered. It is found that the variation of the velocity profiles along the bended pipe is considerable. A determination of the resulting fluid loads on the pipe walls is of interest e.g., for evaluating the dynamical behaviour of lightly damped structures like Coriolis flow meters.

Impinging jets on a plate with a degree of freedom in torsion

12109
Thu·15:05·10

Yohann Nyirumulinga,† Clotilde Regardin, Frédéric Marmonier, Roger Ohayon and Edmond Szechenyi
Conservatoire National des Arts et Métiers, France†

The purpose of this study is to understand the aeroelastic behaviour (flutter and divergence) of metal sheets impacted by high speed cooling jets. A simplified half-scale model of an industrial unit was first developed to simulate the dynamic behaviour of the steel sheets. The aeroelastic stiffness and damping coefficients were measured as a function of a number of parameters. A governing non-dimensional reduced velocity was identified. Among the tested configurations, those that replicated the industrial unit diverged in the expected manner whilst others did not or the divergence was shifted to much higher flow speeds. In order to understand the governing aerodynamic mechanisms a more fundamental experimental rig is being built. It will give the surface mapping of the complex unsteady pressures on a jet-impacted oscillating plate via transfer functions between the motion and the pressures. An integral of these pressures will also yield the total unsteady aerodynamic loads.

Linear analysis of boundary layer flow interacting with a finite compliant surface

10689
Fri·09:15·10

Mark Pitman† and Anthony Lucey
Curtin University of Technology, Australia†

Eigenvalues, vectors and stability information are directly extracted for linear perturbations to a fully viscous, spatially developing, fluid-structure interaction (FSI) system through the development and use of a new method. Here, the FSI system consists of fully developed viscous plane Poiseuille flow interacting with a finite compliant wall section mounted in an otherwise rigid domain. A combination of spectral, finite-difference and discrete-vortex methods is applied to a linear-perturbation form of the full Navier–Stokes equations, couched in velocity-vorticity form, and the one-dimensional beam equation. This yields a system of coupled linear equations that accurately define the spatio-temporal development of linear perturbations to the mean flow-structure system. The results from this method can be used to describe conclusively the role that finite compliant surfaces play in the development of Tollmien–Schlichting (TS) and FSI instabilities across a broad spectrum.

The fluid–structure dynamics of a cantilevered-free flexible plate in a uniform flow

11217
Fri·09:35·10

Anthony Lucey,† Richard Howell and Mark Pitman
Curtin University of Technology, Australia†

A new computational model is developed and used to conduct a comprehensive study of the two-dimensional linear stability of a cantilevered flexible plate in uniform flow. Boundary-element and discrete-vortex methods are combined to model the flow field. The plate is described by a finite-difference form of the beam equation. Stability is assessed by casting the system equation in State-Space form and directly extracting the eigenmodes. In parallel, numerical simulations are performed to reveal localized behaviour within the system and lead to an exposition of instability mechanisms. As flow speed in increased, short plates succumb to single-mode flutter caused by irreversible energy transfer while the critical instability for long plates is a Kelvin–Helmholtz type of modal-coalescence flutter usually found in conservative systems. Within this framework, the effects of the wake, an upstream rigid plate, material inhomogeneity and channel walls are evaluated and interpreted.

Nonlinear mixed-mode lateral vibration of a fluid-conveying cantilevered pipe with an end mass

11301
Fri·09:55·10

Masatsugu Yoshizawa,† Kiyotaka Yamashita, Yuuki Hirose and Junji Ajiro
Keio University, Japan†

We deal with nonlinear lateral vibrations of a fluid-conveying cantilevered pipe that is hung vertically with an end mass. First, the behaviors of a silicon rubber pipe conveying water were observed using the image processing system with two CCD cameras. As a result, the second mode, the mixed-mode and the third mode flutters of the cantilevered pipe were confirmed with increasing the flow velocity. Here the mixed-mode flutter includes the second and third modes simultaneously. Second, the nonlinear-coupled complex amplitude equations of the second and third modes of the pipe vibration are derived with the use of the orthogonal condition between the linear eigenfunctions and their adjoint functions. It is clarified mainly from the theoretical analysis that the amplitudes of the second and third modes correspond to the supercritical and subcritical Hopf bifurcations of pipe vibration, respectively.

Chaotic oscillation during vortex-induced vibration

11539
Fri·10:15·10

Justin Leontini† and Mark Thompson
Monash University, Australia†

Results are presented that show for a small range of flow speeds, the vortex-induced vibration response of an elastically-mounted cylinder is chaotic. This is in spite of the flow being restricted to being two-dimensional. Aside from observation of high amplitudes of response and disordered vortex configurations in the wake, the leading Lyapunov exponent is estimated from the numerical experiment data. The fact that this exponent is positive gives quantitative evidence for the fact that the response is chaotic.

Oscillation onset in collapsible tubes by decreasing external pressure

11719
Fri·11:00·1

Christopher Bertram,† Nicholas Truong and Stephen Hall
University of New South Wales, Australia†

The onset of oscillation in a collapsible tube as the result of reducing the external pressure was studied using particle image velocimetry. The silicone-rubber tube was initially highly collapsed

and measurements were taken as the tube gradually opened and started to oscillate. Changes in whole-flow-field patterns as a result of discrete changes in the control variables were examined, as well as local velocity fluctuations associated with small-amplitude pressure oscillations. Changes in the flow between the two main jets were noted in the lead-up to oscillation. In particular the jet path and profile varied with bulk flow-rate as did the region of low/reverse flow between the jets. By analysing the power spectrum of the instantaneous velocity vectors it was found that fluctuations at the same frequency as the internal pressure fluctuations arose largely in areas near the entrance of the main jet and near the blending region of the jets.

Analytical model for the lift on a rotationally oscillating cylinder

11925
Fri·11:20·1

Muhammad Hajj† and Isam Janajreh
Virginia Tech, USA†

The development of analytical models for the forces on oscillating cylinders would serve in the prediction of vortex-induced vibrations or in the optimization of oscillation patterns for the purpose of drag reduction or lift augmentation. In this work, a general framework for the development of such models for the lift force acting on oscillating cylinders is discussed. A Direct Numerical Simulation of the unsteady incompressible Navier–Stokes equations of the flow is performed to generate the database from which the model parameters are identified. The identification is based on combining amplitude and phase measurements from higher-order spectral analysis of the numerically generated data with approximate solutions of the assumed model. The application of the framework is exemplified through the derivation of an analytical model that simulates the lift on a rotationally oscillating cylinder in the lock-on regime.

Third-order effects in wave–body interaction

10478
Fri·11:40·1

Bernard Molin,† Olivier Kimmoun and Fabien Remy
Ecole Centrale Marseille, France†

Impressive wave run-ups are often observed on the weather side of strongly reflecting structures like vertical breakwaters or offshore barges. These high wave elevations are nor predicted by classical theories. It is demonstrated, through experimental, theoretical and numerical tools, that they are due to tertiary (third-order in the wave amplitude) interactions between the incident and reflected wave systems, the latter acting as a shoal to the incoming waves.

Phase shift effects for fluid conveying pipes with non-ideal supports

10725
Fri·12:00·1

Jonas Dahl† and Jon Thomsen
Technical University of Denmark, Denmark†

Vibrations of a fluid-conveying pipe with non-ideal supports are investigated with respect to phase shift effects. A numerical Galerkin approach is developed for this general problem, and the use of it exemplified with a investigation of phase shift effects from rotational damping at supports of a simply supported pipe. It is found that asymmetric viscous rotational damping at supports gives rise to phase shifts along the pipe which cannot be distinguished from phase shift from mass flow. This is of interest, e.g., for the development and troubleshooting of Coriolis flow meters.

FSM05 :: Granular materials and flows

Chairs: Detlef Lohse (Netherlands) and Tom Mullin (UK)

Thu	09:15–10:35	Hall E	Lectures
Thu	11:00–12:40	Room 8	Lectures
Thu	16:00–17:00	Hall D	Lectures
Fri	11:00–12:00	Room 8	Lectures

Ripple and undulation on vertically vibrated granular layers: dependence on material properties

11729
Thu·09:15·E

Ataka Takei† and Osamu Sano
Tokyo University of Agriculture and Technology, Japan†

Formation of ripple and undulation on the vertically vibrated granular layer is investigated. The particles we tested are glass, aluminum, alumina and lead spheres with various diameter ranging from 0.05 to 0.5 mm. In addition to the dependence on the granular size d and the layer height h, external forcing frequency f and amplitude a, dependence on material properties of the grains, such as the density ρ, effective Young's modulus E^* and Poisson's ratio σ^*, and friction coefficient μ^*, etc are studied. Two models of the dispersion relation that are relevant to fluid and elastic states of the granular material are proposed.

Highly nonlinear solitary waves in periodic granular media

11749
Thu·09:35·E

Chiara Daraio,† Mason Porter, Eric Herbold, Ivan Szelengowicz and Panayotis Kevrekidis
California Institute of Technology, USA†

We investigate the propagation of highly nonlinear solitary waves in periodic arrangements of dimer (two-mass) and trimer (three-mass) cell structures in one dimensional granular media using experiments, numerical simulations, and theoretical analysis. We utilize particles of different materials to vary the composition of the fundamental periodic units in the chain. Employing a model with Hertzian interactions between adjacent beads, we find very good agreement between experiments and numerical simulations. We derive a theoretical analysis for heterogeneous environments (dimer chains) in the long-wavelength regime and find an excellent agreement between the discrete and continuum approach. This analysis encompasses previous studies and provides key insights on the influence of the heterogeneous lattices on the properties of the nonlinear wave solutions of this system. The work paves the road to the study of acoustic band gaps, randomization and localization phenomena in granular media.

Crushing of granular media by a discrete numerical modeling

11813
Thu·09:55·E

Mohamed Guessasma,† Jérôme Fortin, Patrice Coorevits and Adolphe Kimbonguila
Université de Picardie Jules Verne, France†

The crushing process is usually used in many industrial fields, but this process remains economically expensive, essentially due to the energetic cost and the low quality of finished products (heterogeneity of grain sizes or shapes). The goal of this study is the modeling of the fragmentation of granular media subjected to compressive or impact forces by using Discrete Element Method (DEM). The proposed modeling is based on the mechanical behavior of the granular material and damage criterion to predict the grain fragmentations according to the direction of the contact forces. For a better knowledge of mechanical phenomenon, we have studied the influence of the granulometry on the contact force chains distribution and fragmentation modes of grains. The proposed modeling is carried out by performing numerical simulations of granular media under crushing pressure by using numerical software MULTICOR.

A constitutive model for unsaturated granular materials

10763
Thu·10:15·E

Pierre-Yves Hicher† and Ching Chang
Ecole Centrale Nantes, France†

A homogenization technique is used to obtain a constitutive model for unsaturated granular materials. The stress-strain relationship is derived as an average of the mobilization behavior of the local planes at grain contacts in all orientations. The local behavior is assumed to follow a Hertz–Mindlin's elastic law and a Mohr–Coulomb's plastic law. For the non-saturated state, capillary forces at the grain contacts are added to the contact forces created by an external load. They are calculated as a function of the degree of saturation, depending on the grain size distribution and on the void ratio of the granular assembly. Numerical simulations show that the model is capable of reproducing the major trends of a partially saturated granular assembly under various stress and water content conditions.

Influence of particle shape in the statistical mechanics of classical gases

10861
Thu·11:00·8

Fernando Alonso-Marroquin† and Stefan Luding
The University of Queensland, Australia†

The evolution towards statistical equilibrium of a classical system of non-spherical particles is studied using molecular dynamics. Simulations with a large number of particles comply with the basic assumptions of classical statistical mechanics, such as the principle of equipartition of energy, and the Maxwell-Boltzmann statistics for energy distribution.

Computer modelling of doming phenomenon in flow of granular–cohesive material

11029
Thu·11:20·8

Zdzislaw Wieckowski
Technical University of Lodz, Poland

The phenomenon of dome creation during the process of granular flow in a silo is analysed. The doming phenomenon frequently occurs during such processes as silo discharge or reclaiming a granular material from stock-pile—the part of the material located initially over a silo or reclaim tunnel outlet falls down after separation from the rest of the stored material which remains at rest. The phenomenon is modelled by the use of the material point method (MPM) which is an arbitrary Lagrangian–Eulerian formulation of the finite element method (FEM). MPM utilises two kinds of space discretisation: motion of material points is traced with respect to an Eulerian computational mesh which enables to analyse large strains and fragmentation problems with undistorted finite elements. The behaviour of the granular material is described by the elastic–viscoplastic constitutive model with cohesion. The minimum value of cohesion for which doming occurs has been found in an example.

Dense granular materials are Cosserat continua

11187
Thu·11:40·8

Prabhu Nott,† Jaysree Patra and Ananda Sreenivas
Indian Institute of Science, India†

In the regime of dense, slow flow of granular materials, classical plasticity theories have been applied with some success for flow through hoppers and bunkers. However, these theories fail to capture the thin shear layers that are commonly observed, and fail to represent the kinematics of viscometric flows. Some recent studies have attempted to correct this deficiency by treating granular materials as Cosserat continua. Indirect validation of Cosserat plasticity models have been reported, but direct verification of the essential features of a Cosserat continuum has been lacking. Here, we provide experimental verification of an important Cosserat effect, namely the deviation of the spin from half the vorticity, in flow through a vertical channel and a wedge-shaped hopper. Our data shows that this effect is present not just within the shear layer, but also outside it. Significantly, the effect is much stronger in the non-viscometric hopper flow.

Scaling the final deposits of dry cohesive granular columns after collapse and quasi-static fall

11285
Thu·12:00·8

Catherine Meriaux† and Trent Triantafillou
Monash University, Australia†

This paper reports on laboratory experiments that were designed to investigate the collapse and quasi-static fall of dry cohesive granular columns using a powder of Gypsum. In all the experiments, the cohesive granular columns fractured and flowed in coherent blocks but, while faults remained steep in the quasi-static fall experiments, they flattened in the collapse experiments as the initial aspect ratio of the columns increased. Dilation was seen in the quasi-static fall experiments, while some air entrapment within the columns occurred in the collapse experiments. We found that the ratio of initial to final height and final run-out to initial length of the cohesive columns satisfy power law relationships as a function of the initial aspect ratio of the columns like non-cohesive dry sand columns. This outcome agrees with our scaling analysis, which suggests that, except in the limit of the short columns, friction rather than cohesion controlled the flow of our columns.

Thermomicromechanical continuum theory for granular materials

12159
Thu·12:20·8

Antoinette Tordesillas† and Maya Muthuswamy
The University of Melbourne, Australia†

Presented here is a method for the development of thermomicromechanical constitutive laws that are expressed solely in terms of particle scale properties, and thus engenders physical transparency across micro-meso-macro scales. The focus of this study is on dense granular media under quasi-static loading. Micromechanical relations for the internal variables, tied to nonaffine deformation, and their evolution laws are derived from a structural mechanical analysis of a particular mesoscopic event: confined, elastic-plastic buckling of a force chain. The resulting constitutive law can reproduce the defining behavior of strain-softening under dilatation, and strain localization in the context of bifurcation theory. The thickness and angle of, and the distributions of particle rotation and the emergent normal contact force anisotropy inside the band are consistent with DEM simulations.

Computer aided kinetic theory and granular matter

11642
Thu·16:00·D

Isaac Goldhirsch
Tel-Aviv University, Israel

A novel and powerful method for solving the Boltzmann and Enskog–Boltzmann equations for granular gases will be presented. The method is based on a super-generating function that can produce the "matrix elements" of the Boltzmann operator through simple derivatives (that are carried out by a symbolic manipulator). Constitutive relations for monodisperse, polydisperse and frictional granular gases will be presented. Time allowing results for shocks will be presented as well. Among the novel physical results to be shown is a universal sandwich-like arrangement of grains in a vibrated granular mixture and a sizeable streamwise heat flux in a sheared system. The importance of Burnett contributions to some of the presented phenomena will be demonstrated.

Realization of the Smoluchowski–Feynman ratchet in a granular gas

11476
Thu·16:20·D

Devaraj van der Meer,[†] Peter Eshuis, Ko van der Weele and Detlef Lohse
University of Twente, Netherlands[†]

We construct a granular Smoluchowski–Feynman ratchet, consisting of four vanes that are allowed to rotate freely in a vibrofluidized granular gas. The two crucial ingredients of the ratchet are: (i) The out-of-equilibrium environment provided by the gas, to circumvent the second law of thermodynamics, and (ii) the symmetry-breaking provided by applying a soft coating to one side of each vane, such that it obtains a lower coefficient of restitution. The onset of the ratchet effect (i.e., a non-zero average angular velocity) occurs at a critical shaking strength via a smooth, continuous phase transition.

The numerical simulation for a hemisphere colliding into granular material

11466
Thu·16:40·D

Lei Yang[†] and Caishan Liu
China Academy of Space Technology, China[†]

This paper uses the Distinct Element Method (DEM) to study the impact event of a hemisphere colliding into granular materials. In order to lessen the burden of large scales simulation in using DEM, a 2D numerical model for the impact phenomena of a hemisphere is conducted and a scaling rule between 2D and 3D models is developed. Comparisons between numerical results and experimental data for hemispherical penetrometers dropped into soil is carried out and show good agreement.

A multiscale methodology in granular matter physics

10705
Fri·11:00·8

Qicheng Sun[†] and Guangqian Wang
Tsinghua University, China[†]

Granular matter is fundamentally different from both solid and liquid, which is strongly related to complex dynamics of force chain network as reported in recent papers. A multiscale methodology is firstly introduced according to corresponding mechanisms, i.e. microscale at particle size, mesoscale for force chains, and macroscale for the bulk of granular matter. Computer might be merely the last tool to provide insight into granular matter, but one condition would be using reasonable theory. A discrete element model based on rigorous contact theory is proposed to investigate the multiscale properties, and then 12,000 sphere coplanar packing under gravity is simulated. Quantitative analyses of force chains, the mesoscale structure, are made.

Nonlinear stability of granular shear flow: Landau equation and shear-banding

10199
Fri·11:20·8

Meheboob Alam[†] and Priyanka Shukla
Jawaharlal Nehru Center for Advanced Scientific Research, India[†]

The goal of the present work is to explore whether we could describe the shear-banding phenomenon in granular plane Couette flow via an 'order-parameter' equation. Starting from the continuum equations of rapid granular flows, we derived Landau equation for the plane Couette flow using both the amplitude-expansion method and the center-manifold reduction. This amplitude 'order-parameter' equation describes the onset and the subsequent dynamics of shear-band formation near the critical point. Our results on Landau coefficients suggest that there is a sub-critical finite amplitude instability for both dilute and dense flows which agrees with molecular dynamics simulations of granular plane Couette flow.

Pattern formation at a sand bed surface

10338
Fri·11:40·8

Thomas Loiseleux,[†] Philippe Gondret, Delphine Doppler and Marc Rabaud
Lab FAST & ENSTA-ParisTech, France[†]

The destabilisation of a granular bed by a continuous and laminar water flow in a narrow flume is studied. Depending on the flow rate and the slope of the bed, regimes that are reached are dominated by surface erosion and/or avalanches. Above erosion threshold, the granular surface deforms and periodic propagative structures arise. For small slopes—below avalanche threshold—ripples emerge uniformly along the interface. For short times, a slow algebraic growth is evidenced. For long times, their characteristics evolve logarithmically. For large slopes—above avalanche threshold—the competition between avalanche and uphill erosion gives birth to exponentially growing vortex ripples. They rapidly saturate and propagate in the flow direction. Temporal growth rate is sensitive to tilt angle and bead diameter, but not to flow rate. Final amplitudes and wavelengths depend mainly on the pile slope and are correlated suggesting a growth limited by the quantity of avalanching grains.

FSM06 :: Mechanics of material processing

Chairs: Francisco Chinesta (France) and Gabor Stepan (Hungary)

Thu	16:00–17:00	Hall A	Lectures
Fri	09:15–10:15	Room 2	Lectures

Supercritical bifurcation in the state-dependent delay model of turning **11074** Thu·16:00·A

Pankaj Wahi
Indian Institute of Technology, Kanpur, India

Delayed models of self-excited regenerative tool vibrations are generally associated with subcritical Hopf bifurcations However, it has recently been realized that the regenerative delay is determined by a combination of the tool vibration and the workpiece rotation resulting in a state-dependent delay model. In this paper, we analyze the nonlinear dynamics of this state-dependent delay model near the Hopf bifurcation point using the method of multiple scales (MMS). It has been determined that the criticality of the Hopf bifurcation changes from subcritical to supercritical with an increase in the feed rate. The criticality chart separating the regions of subcritical and supercritical bifurcations in the parameter space has been obtained for a range of damping ratios. For a given spindle speed, the minimum feed rate for a supercritical bifurcation decreases with an increase in the damping ratio making it feasible to achieve supercritical nature in physical turning processes.

Apparent coexistence of multiple regimes of self-excited vibrations in deep drilling systems **11130** Thu·16:20·A

Emmanuel Detournay[†] and Alexandre Depouhon
University of Minnesota, USA[†]

Based on a discrete model of a rotary deep drilling system and on physically consistent rate-independent bit-rock interaction laws that account for the regenerative nature of the cutting process taking place at the drill bit level, we present preliminary results regarding the apparent coexistence of multiple drilling regimes. An argument based on a linear stability analysis is provided to justify this feature of the model that matches lab experiments and field observations: slow unstable poles of the linearized system are responsible for a very slow divergent response of the system, which yields apparent coexistence of drilling regimes (stationary, quasi-periodic and stick-slip oscillations) as the system is subject to external perturbations of various magnitudes and types.

Bi-stable region estimations for metal cutting **10580** Thu·16:40·A

Gabor Stepan,[†] Zoltan Dombovari and Eddie Wilson
Budapest University of Technology and Economics, Hungary[†]

The classical model of regenerative vibration is investigated with new kinds of nonlinearities; based on some experimental results, the proposed model includes an essential inflection point in the force characteristics. In case of orthogonal cutting, the existence condition of unstable self-excited vibrations is given along the stability limits, which is related to the force characteristic at its inflection point. An analytical estimation is derived for the chip width where the co-existence of stable stationary cutting and a strange stable self-excited vibration 'outside' the unstable periodic motion is expected. It is shown how this domain of bi-stability depends on the theoretical chip thickness. The comparison of these results to the experimental observations and also to the bifurcation results obtained for standard nonlinear cutting force characteristics provides relevant information on the nature of the nonlinearity of the cutting force.

A study of material behaviour at large plastic strains using plane-strain machining with a wedge indenter

11511
Fri·09:15·2

Tejas Murthy,† Christopher Saldana, Ravi Shankar, Srinivasan Chandrasekar, Dale Compton and Kevin Trumble
Purdue University, USA†

It is shown using direct measurements that the deformation field in plane-strain machining, which involves material removal by a sliding wedge indenter, is characterized by large plastic strains ($\sim$ 1–10) and strain rates of 1–10^5/sec. These parameters can be varied systematically by adjusting the wedge angle and sliding speed, thus making machining an attractive method of Severe Plastic Deformation (SPD). This SPD method accesses a region of deformation parameter space that is complementary to existing mechanical tests such as tension/compression, split Hopkinson bar and plate impact. The application of the method to study the interactive effects of strain, strain rate and temperature on large deformation phenomena, including microstructure refinement, is demonstrated using studies on model material systems.

Supercritical bifurcations in the state-dependent delay model of turning process

11550
Fri·09:35·2

Tamás Insperger,† Gábor Stépán and David Barton
Budapest University of Technology and Economics, Hungary†

Nonlinear dynamics of a state-dependent delay model of the turning process is analyzed. A numerical continuation technique is used to follow the periodic orbits of the system. It is shown that both sub- and supercritical Hopf bifurcations occur in the model, and the criticality depends on the feed rate. This is in contrast to simpler constant delay models where only subcritical Hopf bifurcation occurs independently on the feed rate.

Numerical simulation of friction stir welding processes

11326
Fri·09:55·2

Elias Cueto,† Arnaud Poitou, François Gratecap, Iciar Alfaro and Francisco Chinesta
University of Zaragoza, Spain†

In this paper we present a numerical model for the simulation of friction stir welding (FSW) processes. FSW is a solid-state welding process based upon the mixing provoked by a rotating pin that is forced to move between the pieces to join (usually plates). The model employs the natural element method (NEM), a member of the vast family of meshless methods, to perform simulations in an updated Lagrangian approach. This avoids the burden associated with remeshing in traditional Eulerian or arbitrary Eagrangian–Eulerian (ALE) approaches to this same problem. The method allows to understand the flow patterns that lead to the formation of layers during the welding. Experimental results that confirm the presence of chaotic flow will also presented.

FSM07 :: Porous media

Chairs: Wolfgang Ehlers (Germany) and Dominique Salin (France)

Tue	15:05–15:10	Room 8	Seminars
Wed	10:40–13:00	Hall E	Lectures
Thu	16:00–17:00	Hall E	Lectures

Simulation of carbonate matrix acidizing **10723** Tue·15:05·8

Bulgakova Guzel,† Alexey Telin and Aygul Kamaltinova
Ufa State Aviation Technical University, Russia†

Models of near wellbore region acidizing at pressures below the parting pressure of formation are constructed: one-dimensional model of a wormhole and stochastic model of dissolution structure. In one-dimensional case in wormhole model it is supposed that the growth direction of dissolution structure is known, and the axis of model is the axis of a wormhole. Results of wormhole modeling were compared to experimental data of one of Russian oil fields. In the two-dimensional case, it is impossible to predict a growth direction as dissolution process has stochastic nature, therefore the dissolution structure is considered as fractal. Stochastic model is based on model of dielectric breakdown. On models various characteristics of dissolution structures depending on Damköhler number defined as ratio of convection time to reaction time and Péclet number defined as ratio of diffusion time to convection time were investigated, also acidizing optimum technological parameters were investigated.

The tip of a fluid-driven fracture in a permeable elastic medium **10174** Wed·10:40·E

Yevhen Kovalyshen† and Emmanuel Detournay
University of Minnesota, USA†

We study the tip region of a fluid-driven fracture in a permeable elastic medium, by considering the stationary problem of a steadily moving semi-infinite hydraulic crack. The problem accounts for the existence of a tip cavity filled with pore fluid sucked from the porous medium, the build-up of a low-permeability cake on the walls of the fracture associated with leak-off of the fracturing fluid, and hydraulic diffusion in the surrounding medium. The problem depends on 5 dimensionless parameters. Near- and far-field asymptotic solutions, as well as numerical solutions are constructed.

Swelling phenomena in chemically active hydrated materials **10333** Wed·11:00·E

Wolfgang Ehlers,† Nils Karajan and Ayhan Acartürk
University of Stuttgart, Germany†

Hydrated materials exhibit internal coupling mechanisms stemming from the characteristics of the constituents. The presented model consists of a fluid-saturated solid matrix carrying volume-free fixed negative charges, while the pore fluid is given by a mixture of a liquid solvent as well as cations and anions of a dissolved salt. Based on the Theory of Porous Media, the governing equations are the volume balance of the fluid mixture, the cation concentration balance, the overall momentum balance and the electrical continuity equation. The solid extra stress is described by an extended neo-Hookean law, while the fluid flow follows an extended Darcy's equation including the gradients of the ion concentrations and the electrical potential. The ion diffusion is described by an extended Nernst–Planck equation. Numerical examples proceed from mixed finite elements, where boundary conditions depending on internal variables are included by certain numerical stabilisation techniques.

Stress measures in partially saturated porous media mechanics **11313** Wed·11:20·E

Bernhard Schrefler,[†] Francesco Pesavento and William Gray
University of Padova, Italy[†]

The paper deals with stress measures in partially saturated porous media mechanics. In soil mechanics today the most commonly used stress tensor is the generalized Bishop stress. However in other porous media this form of the stress tensor is not optimal. For instance it is not accurate enough when simulating drying/shrinkage in concrete. In an effort to obtain a thermodynamically consistent form of a more suitable stress tensor averaging theory for phase properties, interface properties and system thermodynamics is used to provide a consistent framework for sorting out appropriate definitions for the involved quantities. This has allowed to obtain a form of the solid stress tensor which satisfies the Hill–Mandel condition and to clarify the meaning of the solid pressure and of the Biot constant. Finally a stress tensor for partially saturated porous media is obtained that resembles the Bishop–Skempton stress tensor and is thermodynamically consistent.

Simulation, modelling and measurement of dispersive flow in bead packs **11410** Wed·11:40·E

Howard Davis,[†] Kroll Daniel, Maier Robert, McCormick Alon and Vandre Eric
University of Minnesota, USA[†]

Pore-scale simulations of flow and transport offer the possibility of modeling laboratory-scale experiments without averaging the properties of the porous medium. Using such simulation methods we have predicted bead diameter-dependent solute dispersion in cylindrical beadpacks. Aris–Taylor analysis reveals that radial heterogeneities in porosity and velocity cause the dependency. Experiments support the predictions.

Wave propagation in partially-saturated rocks: theoretical and numerical investigation **11499** Wed·12:00·E

Holger Steeb[†] and Stefan Schmalholz
Saarland University, Germany[†]

The paper discusses wave propagation in partially-saturated rocks. A novel mixture-theory based three-phase model is proposed and analyzed with respect to its phase velocities and attenuation effects. The paper is closed with a Galerkin finite element implementation in the time domain and several numerical investigations comparing classical models with the three-phase approach.

Effect of vibrations on stability of displacement front **11628** Wed·12:20·E

Dmitriy Lyubimov,[†] Oleg Zikanov, Grigoriy Sedelnikov, Tatyana Lyubimova and Andrey Ivantsov
Perm State University, Russia[†]

We study vibration effect on stability of liquid-liquid interfaces in porous media for two cases: a plane displacement front and a falling spherical droplet. The problems are solved for finite frequency vibrations and in the asymptotic limit of high frequency. The transport in porous media is represented by the Darcy filtration model with additional inertial terms. Simulation of the nonlinear interface deformations is conducted using the level set approach. It is found that vibrations can suppress short-wave perturbations of the displacement front, i.e. the perturbations that are most unstable in the classical non-vibrating case. It is also shown that, in the presence of weak vertical vibrations, similarly to the non-vibrating case, the droplet is unstable to small-scale perturbations localized near the one of the poles. Stronger vibrations can suppress the instability entirely. Further growth of the vibration strength leads to another instability, localized near the droplet equator.

A micromechanical modeling of poroplastic behaviour of saturated microcracked media

11880
Wed·12:40·E

Djimédo Kondo,† Qizhi Zhu, Jian-Fu Shao and Vincent Monchiet
Laboratoire de Mécanique de Lille, France†

We propose a 3D micromechanical model of the poroplastic behaviour of saturated microcracked materials. The porous medium is made up of a perfectly plastic matrix containing prolate or oblate microcavities (including microcracks) saturated by a fluid under pressure. In order to derive the macroscopic yield function, we use a limit analysis approach of the porous material in which an original Eshelby solution-based trial velocity field is considered. The obtained anisotropic pressure-sensitive yield function presents several original features. First, it is valid for arbitrary loadings and validated by comparison with numerical solutions. Significant improvements of existing criteria are shown, notably in the case of saturated penny-shaped cracks. Secondly, it is shown that the anisotropic behavior of the saturated poroplastic damaged materials is controlled by an effective stress. This has eased applications of the model to a geomechanical project coordinated by the French agency Andra.

The three characteristic behaviours of dual-porosity media

11543
Thu·16:00·E

Pascale Royer,† Jean-Louis Auriault and Claude Boutin
Laboratoire de Mécanique et Génie Civil, France†

Homogenisation of consolidation, transient fluid flow and solute transport in dual-porosity media has highlighted the existence of three characteristic macroscopic behaviours. The present paper is aimed towards presenting the original result that consists of relating each type of behaviour to a specific relationship between two characteristic times. The result is valid for any phenomenon.

Exact infiltration under concentration boundary conditions

10876
Thu·16:20·E

Philip Broadbridge
University of Melbourne, Australia

Integrable nonlinear convection-diffusion equations have previously been used to obtain realistic one-dimensional solutions for transient unsaturated flow in soil subject to constant-flux boundary conditions. However the solution with constant-concentration boundary conditions has defied our best efforts. This problem can be transformed to the standard Stefan problem for solidification, with latent heat release, linear heat conduction and additional steady heat extraction occurring at the free boundary. The standard scale-invariant Neumann solution is the leading term of the early-time solution, which neglects the steady heat extraction. If we choose independent coordinates to be canonical coordinates of the scaling symmetry, then separation of variables is admissible at all levels of correction for the non-invariant problem. The full solution is a power series in square root time, for which remarkably, each term satisfies the governing equation.

10205
Thu·16:40·E

Kinetic theory for suspension/colloid flow in porous media

Pavel Bedrikovetsky,† Oleg Dinariev and Luiz Rego
The University of Adelaide/PETROBRAS, Australia†

Filtration of colloids/suspensions in porous media occurs in environmental, chemical and petroleum engineering. The main features are particle capture and rock clogging. Several contradictions in the classical deep bed filtration theory and its deviation from laboratory data motivate deriving the model from micro scale physics. State of the flowing suspension in porous media can be described by probability distribution function (PDF) for particle velocity. The relationship between PDFs for particle velocity and for pore radius is discussed. The natural assumptions result in linear BGK version of Boltzmann?s equation. The homogenisation was performed by solving the operator equations in Hilbert space of Fourier images. The obtained large scale model significantly differs from the classical system. Two particular flow cases are paradox-free for the new model. Applications of results to propagation of contaminants in aquifers and to formation damage evaluation in oilfields are discussed.

FSM08 :: Education in mechanics

Chairs: Igle Gledhill (South Africa) and Carl Herakovich (USA)

Mon	16:25–17:45	Room 3	Lectures
Thu	09:15–10:35	Hall B	Lectures

Some outstanding events and persons in the history of mechanics **10337** Mon·16:25·3

Olga Kryuchkova† and Alexander Olshevsky
Bryansk Open Institut of Business and Management, Russia†

The understanding of historical roots and consistent pattern of science development is one of the most foundational aspects of studying any science and educational process. The knowledge of historical background could have a dramatic effect in establishing of a young scientist. The development of mechanics as a science is observed throughout four periods of its history, from Ancient Greece till nowadays. The 1st period is the time of initial knowledge accumulation. The 2nd period was the time of formation of basic ideas and laws of mechanics. Ideas of that phase paved the future blossom of classical mechanics. During the 3rd period the formation of principle basics of the science was finished. The 4th period is the time of mutual penetration of mechanics and other sciences. It last nowadays. In each period the outstanding persons effected the direction of mechanics development cardinally, the accents are made on their personal role in science establishing.

Practical study for vehicle dynamics **10781** Mon·16:45·3

Yoshio Kano,† Takashi Kawaguchi and Masato Abe
Kanagawa Institute of Technology, Japan†

The Department of Vehicle Engineering was reorganized from System Design Engineering in 2006 as the first department of University in Japan in which the students learn mechanical and automotive engineering much more towards professional career in the automotive industry. Because an automobile is a good example for the subjective product due to its wide integration of the engineering and technologies, students have good motivation to study engineering. Standing upon that basic point for the Product Oriented Engineering Education (POEE) in opposite to the conventional education system of philosophy, hands on education program such as practical course, student work and project course are provided to the undergraduate students collaborating with conventional lecture crass. For example, the desktop tire force testing facility, two dimensional suspension kinematics model, and ridged steering vehicle model are shown in this paper.

Design and use of supplementary software for an undergraduate program in engineering science and mechanics **10850** Mon·17:05·3

Glenn Kraige,† Scott Hendricks and Don Morris
Virginia Tech, USA†

In order to partially deal with the demands of 3000 students per year taking traditional mechanics service courses in large sections, along with departmental course considerations, the Department of Engineering Science and Mechanics at Virginia Tech has developed supplementary lecture software for statics, dynamics, mechanics of deformable bodies, and upper-level vibrations and dynamics courses. Software platforms include Flash, Visual Basic, and Matlab. The overall goal is two-fold: To aid the instructor in the large lecture halls and to give the students online access to what has been presented in the lecture. A major consideration is to help the student visualize motion/deformation and appreciate the effect of changes in motion/deformation conditions. The result of recent student surveys is provided.

Photoelasticity as a teaching aid for the finite element method

10894
Mon·17:25·3

Schalk Kok
University of Pretoria, South Africa

Photoelasticity is used as a teaching aid for an undergraduate finite element (FE) course. Experiments are performed on a plane and circular polariscope, using 2D samples of complex geometry. Isoclinic and isochromatic images are captured using a digital camera. Instead of manipulating these images to obtain strain contours, the FE method is used to create numerical isoclinics and isochromatics. This is achieved by modifying a provided Matlab FE code to compute principal strains and principal strain directions. Exceptional agreement is obtained between the experiment and the FE results. This convinces students that the FE method is indeed an accurate and reliable method.

Teaching the modelling of structures

10979
Thu·09:15·B

Juha Paavola† and Eero-Matti Salonen
Helsinki University of Technology, Finland†

The present paper proposes a novel method to teach the modelling of structures. The incoherence in formulating various problems traditionally has often made learning too complicated. The proposed idea is based on reorganization of various themes so that similar tools can be applied when formulating any problem. Particularly, the approach used in numerical and analytical analyses has been different. The use of geometrical and kinematical models is expanded, combined with basic vector calculus. The basic tools, like a local Cartesian frame and principle of virtual work, picked up from computational methods, are proposed to be interlocking concepts.

Class participation experiments in mechanics: two-force members

11333
Thu·09:35·B

Richard McNitt
The Pennsylvania State University, USA

Class participation experiments for two-force members: one in “Statics”, one in “Strength of Materials” are discussed. The example from Statics involves “building” an 18 ft truss from six ft long pieces of polystyrene and some ropes. The SOM example involves use of a cantilever beam (meter stick) to determine section modulus, then determining the Euler buckling load for the meter stick, verifying answer with a small household scale and then demonstrating the benefits of supporting the center of the column. Teachers attending this lecture/demonstration will be prepared to incorporate either of these into their lecture/recitation EM classes

The use of simplified strain gradient elasticity in structural analysis

11398
Thu·09:55·B

Antonios Giannakopoulos† and Ioannis Vardoulakis
University of Thessaly, Greece†

The simplified strain gradient elasticity is applied in structural analysis of thin-walled cross section beams. In the first example, the classic beam is revisited, using a T-type cross-section. The double forces described by the strain gradient elasticity can be interpreted from the shearing of the horizontal flange. In the second example, the open-section Vlasov beam in torsion is revisited, using an I-type cross section. The double torsion can be interpreted from the constraint effects on the warping of the cross-section. It is shown that a non-local estimate of the mean value of the angle of twist of the beam leads to a shear gradient that is energetically consistent with a torsion bi-moment. The proposed models are expected to be useful in micro- and nano- technology. The examples hinder the important issue of non-local differentiation in the averaging theories of Mechanics and serve in understanding the concepts of double forces and double moments.

Promoting education of applied mechanics by mechanics contest

11430
Thu·10:15·B

Nelson Chen,† Ching Chen and Huei-Huang Lee
National Science and Technology Museum, Taiwan†

In order to promote applied mechanics education, a conventional written test for mechanics contest, hosted by STAM, has been taken place for several years. The contest pattern has been changed from the conventional written tests to experiment-oriented tests after the NSTM started to hold the contest event since 2005. The major change of the mechanics contest is to integrate theory into hands-on experiments for more than 200 students at a single location simultaneously. NSTM set up a well-designed video show and materials pack for hands-on experiments for the mechanics contest. The mechanics contest was also highly recommended by the school teachers because it has been very educational to visit mechanics exhibits inside the NSTM during the time when the mechanics final contest was held. Mechanics education has been promoted in both Taiwan and China for past years, partly due to the continuing academic exchanges of mechanics field between Taiwan and China.

FSM09 :: Foams

Chairs: Stelios Kyriakides (USA) and Andrew Kraynik (USA)

Thu	11:00–13:00	Hall E	Lectures

Viscoelastic properties of open cell Kelvin foams

11224
Thu·11:00·E

Heinz Pettermann,† Mathias Luxner, Jürgen Stampfl, Daniel Vallejo and Jaime Dominguez
Vienna University of Technology, Austria†

Open cell Kelvin structures are investigated with respect to their anisotropic viscoelastic properties, in particular the relaxation and damping behavior. The study is concerned with the effective behavior which results from the bulk material as well as the cellular architecture. Finite Element Method simulations of three-dimensional structures are employed to predict the effective response to a wide range of loading modes. In parallel, experimental tests are performed on samples which are produced by Rapid Prototyping. The computational predictions as well as the experimental results are given in terms of relaxation functions for quasi-static loading cases and in terms of frequency dependent damping behavior for cyclic loading scenarios.

Structure and rheology of wet foams

11492
Thu·11:20·E

Andrew Kraynik† and Douglas Reinelt
Sandia National Labs, USA†

The cell structure and rheology of wet foams under quasi-static conditions is modeled with the Surface Evolver for various spatially periodic systems: 1) bulk foams ranging in complexity from ordered (Kelvin, FCC, and Weaire–Phelan) to random structure, and 2) thin layers of ordered foam confined between parallel plates. All of the liquid is assumed to be located in traditional Plateau borders, which form a continuous network of channels along cell edges, or in wall Plateau borders that are adjacent to the plates. In the “dry” limit, one confined layer is composed of hexagonal cylinders; two layers contain Fejes–Toth (modified Kelvin) cells; and three or more layers contain Kelvin cells sandwiched between Fejes–Toth. Results for thin layers provide a relationship between the 2D structure at the wall and the bubble radius, which is relevant to foam characterization. This presentation will focus on elastic behavior and the difference between ordered and random foams.

On the crushing of metallic open-cell foams

10971
Thu·11:40·E

Wen-Yea Jang† and Stelios Kyriakides
University of Texas at Austin, USA†

The compressive stress-displacement response of Al-open cell foams consists of an initial stiff, linear branch; that terminates in a limit load and is followed by an extensive load plateau that ends with a second stiff branch. Using a combination of experiment and analysis it was established that the limit load is due to plastic action. X-ray tomography showed that cells start to buckle and collapse locally, forming a band. Contact limits the extent of local collapse and facilitates its spreading at a nearly constant load. The foam is idealized to be periodic using Kelvin cells with straight ligaments and triangular cross sections that vary along the length. The initial elastic response and the limit load instability have been established using characteristic cell-type models discretized with FEs. The localization of deformation, its spreading and the associated stress plateau are reproduced using large scale finite size type models involving a large number of cells.

Investigation of the representative volume element size and analysis of the deformation mechanisms of open-cell foams **11205** Thu·12:00·E

Anthony Burteau,† Jean-Dominique Bartout, Franck Nguyen, Samuel Forest, Yves Bienvenu, Shadi Saberi and Dirk Naumann
Mines de Paris—ParisTech, France†

In this work, we aim to determine the Representative Volume Element size for open-cell foams as well as to characterize their mechanism of deformation. These 2 aspects are based on X-ray tomography data, used either to build meshes of real foam structures either to perform 3D image analysis. The numerical simulations bring partial answers about the RVE size. With the 3D image analysis, we can access to information at the microscale like the strut length or the cells orientation.

Multi-scale modelling of fracture in metal foams **10059** Thu·12:20·E

Patrick Onck† and Kodanda Mangipudi
University of Groningen, Netherlands†

The overall fracture behaviour of metal foams depends sensitively on the microstructure of the cell-wall material and on the foam's cellular architecture, e.g. the cell size and shape distribution, the cross-sectional geometry of the strut, and its relative density. The goal of this work is study these dependencies using a multiscale modelling framework that takes all these ingredients into account. The model is based on a Voronoi representation of the cellular microstructure, in which the elasto-plastic-fracture behaviour of the strut wall material is accounted for. The results will be presented in terms of scaling relations, relating overall plastic/fracture behaviour to the microstructural parameters as a function of density. Special emphasis will be placed on the effect of the specimen size and the distribution of brittle struts on the overall failure profile.

Pressure-driven and free-rise foam flow **10621** Thu·12:40·E

Lisa Mondy,† Rekha Rao, Christopher Brotherton, Christopher Bourdon, Mathias Celina, Anne Grillet and Sarah Leming
Sandia National Laboratories, USA†

To provide vibration isolation of electronic components, we are interested in the flow of foams through complex geometries. In the current process, epoxy mixed with a liquid blowing agent is injected into a mold, then a foam is formed by boiling the blowing agent in situ. Often voids occur in the finished part because the foam does not fill the fine-scale features of the mold. Finite element computational modeling using a continuum constitutive equation for the foam shows that pressure-driven flow of pre-foamed material may lead to better filling. To support this modeling, a series of experiments has been undertaken to help us understand the stability and flow properties of model foams. Microfocus video is used in conjuction with particle image velocimetry (PIV) to elucidate the boundary condition at the wall. Rheology and density measurements complement the flow visualization. Comparisons to literature predictions of foam rheology and current computations will be described.

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