9th AUSTRALASIAN
FLUID MECHANICS CONFERENCE
AUCKLAND, 8-12 DECEMBER 1986

Measurement of Instantaneous Velocities in Separated Flow around a Bluff Body using Laser Doppler Anemometry

L. W. WELCH[1], C. CARRA [2] and K. HOURIGAN[1]

[1]Commonwealth Scientific and Industrial Research Organisation, Division of Energy Technology, Victoria 3190, Australia.
[2]Department of Mechanical Engineering, Monash University, Victoria, 3168, Australia.

ABSTRACT

At high Reynolds-numbers the flow around a square edged plate will separate from the leading edge corner, reattach downstream and give rise to regions of concentrated vorticity embedded in irrotational fluid. Work at CSIRO has shown that the large scale structures shed from the separation bubble have a strong tendency to combine and further that the rate of shedding and the tendency to combine into paired structures can be regulated by the introduction of sound-induced velocity perturbations. The paper describes the use of a single component Laser Doppler Anemometer, in conjunction with sound-induced velocity perturbations, to measure two-dimensional velocity vectors in the region of the separation bubble by conditionally sampling with respect to the acoustic frequency.

INTRODUCTION

Over the past decade there has been a steady increase in the application of Laser Doppler Anemometry to the measurement of fluid flow. Such measurement techniques are well suited to steady state and stable periodic structured flows, where streamlines or velocity time histories can be determined from instantaneous velocity measurements.

The non-obtrusive nature of LDA would seem well suited to measurements in turbulent flow regions. However, turbulent flow patterns cannot be readily determined from instantaneous velocity measurements; high frequency sampling is only practical over short time periods, simultaneous 2 channel measurement is required, uniform seeding of flow is difficult to obtain and velocity bias errors add to the measurement uncertainty. There are turbulent flows which exhibit a periodic component. In some cases it is possible to describe these flows by relating them to the periodic component using conditional sampling.

In the case of a high Reynolds number flow passing a bluff body (Kiya and Sasaki, 1985), there is normally little or no regular periodic component. The flow separates at the sharp leading edge, reattaches downstream and gives rise to regions of concentrated vorticity embedded in irrotational fluid. Work at the CSIRO (Hourigan et al., 1985), using both numerical and experimental methods (hot-wire probes), has shown that the large scale structures shed from the leading edge separation bubble have a strong tendency to combine. The rate of shedding and the tendency to combine in pairs can be regulated by sound induced velocity perturbations.

The instantaneous velocities in the region about a bluff body can be considered to comprise of three components: a time-mean component; a constant amplitude periodic component; and a fluctuating velocity of varying amplitude and frequency. The periodic component is generally much smaller than the fluctuating component. However, if through the application of spund the periodic component can be increased and it becomes greater than the fluctuating component, then instantaneous measurements can be phase related to the periodic cycle. In the region of the leading edge, the periodic cycle corresponds to the applied acoustic frequency while further downstream it corresponds to half the applied frequency.

The paper describes the use of LDA, in conjunction with sound induced velocity perturbations, to map flow velocities at various phases of the acoustic cycle: attention is focussed on the region of the leading edge separation bubble. This work is part of a combined approach using both numerical and experimental methods to investigate fluid flow and thermal gradients associated with forced convective heat transfer.

EXPERIMENTAL APPARATUS

The test apparatus consists of three major elements, the open jet wind tunnel, the bluff body and sound field, and the laser doppler equipment, Figure 1.

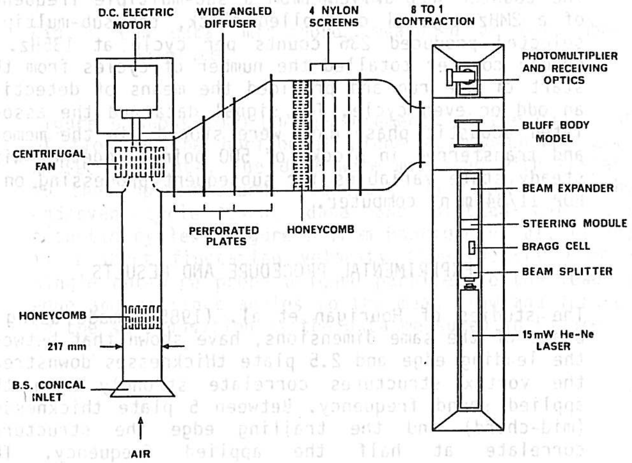

Fig 1: Layout of wind tunnel and laser anemometer

The centrifugal fan of the wind tunnel is powered by a direct current electric motor with variable speed thyristor control. A wide angle diffuser containing four perforated plates connects the fan outlet to a settling chamber containing a honeycomb and four nylon screens. Air leaving the chamber is passed through an 8 to 1 contraction to create, at the exit, a 244mm square open jet working section. The velocity profile is uniform, within 1%, between the boundary layers, which are approximately 3mm thick at the outlet. The centre line longitudinal relative turbulence intensity is 0.3% with the major spectral components occuring below 20Hz. The total volume flow is monitored using a British Standard conical inlet connected to the fan inlet.

The square edged test plate, 13mm thick, 135mm span and 130mm chord, was machined from a block of aluminium alloy. The plate was located midway between two speakers which were positioned 350mm apart. The speakers were connected in anti-phase to generate the equivalent of an acoustic Parker β-mode near the plate, (Parker and Welsh, 1983). This generated a maximum sound pressure level midway between leading and trailing edges that resulted in zero acoustic velocity at the mid-chord position on the plate's surface and a maximum velocity at the leading and trailing edges. For all work described in the paper sound was applied at 135Hz, corresponding to a Strouhal number of 0.2, (sound frequency * plate thickness/upstream velocity), for a mean free stream velocity of 8.77m/s. The sound pressure level was adjusted to 115dB (Re 20μPa) at the mid-chord position on the plate surface. Glass endplates at the spanwise extremities ensured a two-dimensional sound field. The plate/speaker assembly was mounted on a machine table that allowed precise traversing of the assembly in each of the three major axes relative to the fixed laser measurement control volume.

The 15mW Helium-Neon laser and the associated optics were mounted on an optical bench attached to a rigid steel sub-frame. Standard TSI optics were used throughout and included a Bragg frequency cell, a beam expander unit and a high efficiency photo-multiplier. These were configured in the dual beam, single component, forward scatter mode. The flow was very lightly seeded by the introduction of smoke from a 'Concept' smoke generator into the conical inlet. Light scattered from particles, approximately 0.5 micron diameter, passing through the control volume was focussed onto the photo-multiplier and the resulting output interpreted by a TSI counter type, signal processor.

An 8 bit Z80 based micro-processor controlled the action of the counter processor and related the data to the phase of the acoustic cycle of the applied sound. The acoustic phase was determined by a 256 bit counter, reset at the start of each acoustic cycle. The counter was driven from a sub-multiple frequency of a 2MHz crystal controlled clock, the sub-multiple selected produced 236 counts per cycle at 135Hz. A second counter totalled the number of cycles from the start of the run and provided the means of detecting an odd or even cycle. The signal data and the associated acoustic phase data were stored in the memory and transferred in blocks of 500 points together with steady state variables for subsequent processing on a PDP 11/34 mini computer.

EXPERIMENTAL PROCEDURE AND RESULTS

The studies of Hourigan et al. (1985), made using a plate of the same dimensions, have shown that between the leading edge and 2.5 plate thicknesses downstream the vortex structures correlate strongly with the applied sound frequency. Between 5 plate thicknesses (mid-chord) and the trailing edge the structures correlate at half the applied frequency. The transition between the two is not sharp and varies with the height above the plate.

The results presented in this paper have been obtained from measurements in the region between 5mm in front of the leading edge and 25mm downstream of the leading edge and at heights to 20mm above the plate. In this region the application of sound results in a one to one correspondence of the vortex shedding frequency with the applied acoustic frequency. Therefore velocity vectors measured, using a single component LDA, with respect to acoustic cycle can be related to the shedding process. Phase related data measured over many cycles can be averaged and the vector summation of averaged components used to determine the two-dimensional velocity vector for the selected acoustic phase.

Wherever possible two component measurements were made. At heights of 6mm or above the measurements were made in directions parallel to and normal to the surface. Within 2mm of the surface the measurements were made for a single component taken parallel to the plate. The correlation with acoustic frequency for each data set, consisting of one component, one position and 2000 points, was checked by producing a line printer histogram. This histogram showed the magnitude and the number of samples associated with the periodic component. These confirmed that good correlation exists outside the separation bubble; within the bubble, the correlation decreases as the leading edge is approached.

Outside the separation bubble the periodic component represents a very small fraction of the total velocity vector. The magnitude and relative phase of the periodic components becomes clearer if the local mean is removed. For convenience the 236 phases have been regrouped in bins of eight, corresponding to approximately 12 degree intervals.

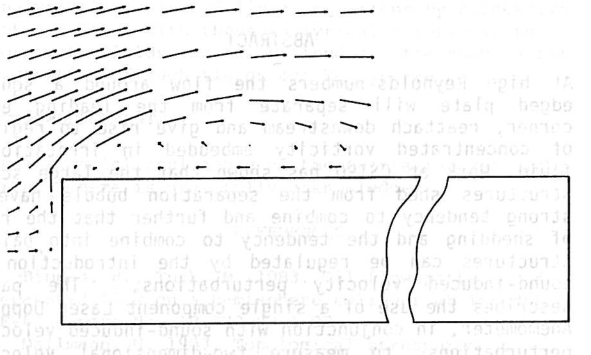

Fig 2: Local mean velocity vectors

Figure 2 shows velocity vectors of the local time-mean flow. The vectors are normalised with respect to the freestream velocity of 8.8ms^{-1}. The vector shown in the upper top left of the figure, is approximately the same in magnitude as the freestream. The increasing magnitude of the vectors for positions downstream of the leading edge show clearly the acceleration of the fluid as it passes over the separation bubble, as discussed by Ota and Itasaka (1976). Close to the surface the mean flow is in the reverse direction and indicates recirculation.

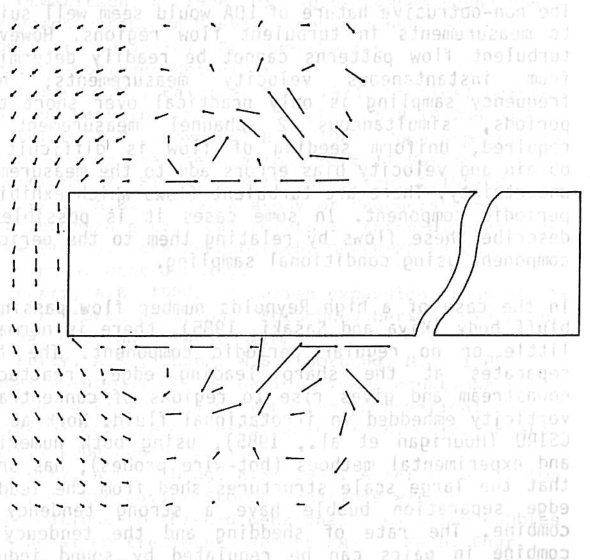

Fig 3: Periodic velocity vectors at phase of maximum acoustic particle velocity

Figures 3 and 4 show the periodic components of the flow at the two phase positions of 150 degrees and 246 degrees (taken at the centre of each bin), respectively; the vector scale is 5 times that of Figure 2. The phase of 150 degrees corresponds with the maximum applied downwards acoustic velocity. At the phase of 246 degrees, approximately quarter of a cycle later, the acoustic velocities approach zero. Because of symmetry, velocities on the underside of the plate can be represented by measurements from the top of the plate with a 180 degree phase shift.

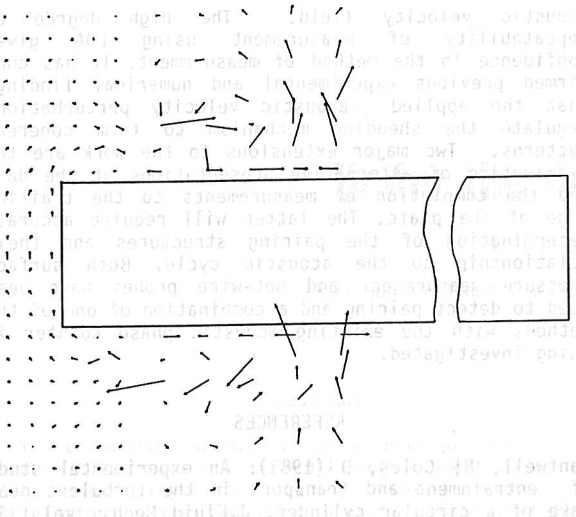

Fig 4: Periodic velocity vectors at phase of minimum acoustic particle velocity

In front of the leading edge the periodic vectors, both in magnitude and direction, correspond closely with the applied acoustic particle velocity in the absence of flow. Downstream of the leading edge the periodic and acoustic vectors are not directionally similar and the periodic vectors are much greater in magnitude.

Close to the surface of the plate, both top and bottom, there are positions at which adjacent periodic components are in opposite directions. There are similar positions on the plane 15mm from the plate surface, but here the vectors lie normal to the plate surface. These patterns develop close to the leading edge and, after an initial retardation, travel downstream at approximately 0.4 of the freestream velocity. These periodic structures are associated with the large scale vortex structures which, following their release from the separation bubble, must accelerate to reach the predicted and observed velocity of 0.75 of the freestream velocity further downstream.

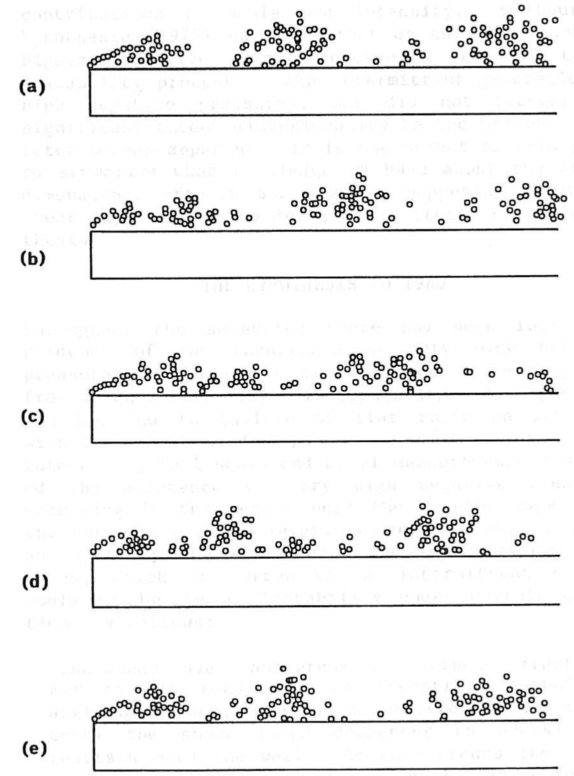

Fig 5: Sequence of plots of elemental vortex positions over two sound cycles at half sound cycle intervals

The removal of the local mean permits direct comparison with the acoustic particle velocities. However, alternative presentations can be more informative in describing flow structures, e.g. critical point theory (Perry et al., 1982; Cantwell and Coles, 1983), and will be considered when the measured data set has been extended to the trailing edge.

Hourigan et al. (1985) have shown that vortex structures leaving the separation bubble have a strong tendency to pair. The sequence shown in Figure 5 shows the development of the pairing process and was produced using the discrete vortex model described by Hourigan et al. (1985). The sequence shows that the elemental vortices representing the shear layer attempt to roll up into a large scale structure each sound cycle. These structures then merge near the point of mean reattachment to form larger paired structures.

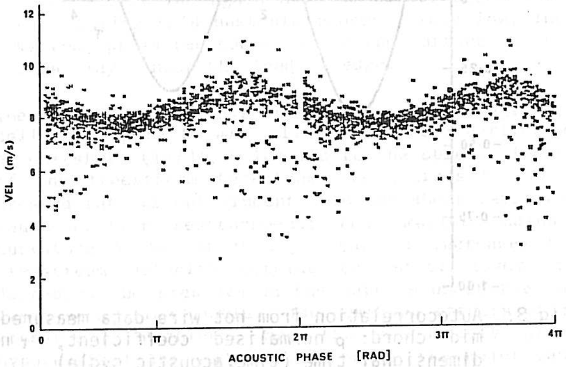

Fig 6: LDA data, mid-chord, measured at 20mm above the plate

Figure 6 shows 2000 LDA measurements of the component of flow in the horizontal plane at mid-chord, 20mm above the plate. The data were measured with respect to the applied sound frequency, separated using the odd/even cycle count data and plotted over two acoustic cycles. Figure 7 from Hourigan et al. (1985) is a short fluctating velocity time history from a single hot-wire probe aligned parallel to the leading edge and at right angles to the mean flow and located in the same position as the data measured in Figure 6.

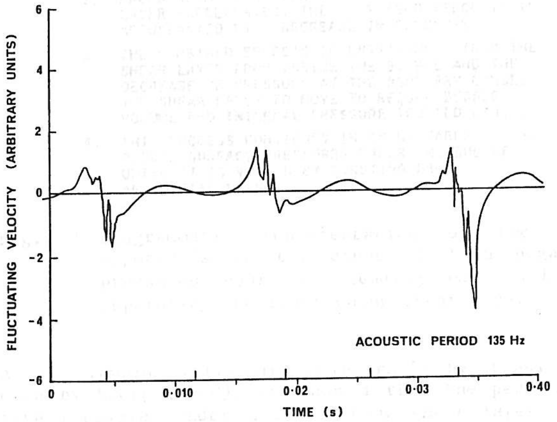

Fig 7: Fluctuating component of hot-wire probe measurement, mid-chord, 20mm above the plate

The composite odd/even cycle data shown in Figure 6 does not correctly represent the phase relationship of velocities within the paired structures. The composite odd/even cycle method fails because there are occasions when two consecutively formed vortex structures fail to pair. Subsequent pairing then continues 180 degrees out of phase with the previous pairings.

This intermittent, alternating nature of the pairing process reduces the magnitude of the half frequency correlation, as shown in Figure 8. Consequently, direct detection of the paired structures will be required if good conditional sampling is to be achieved in this region.

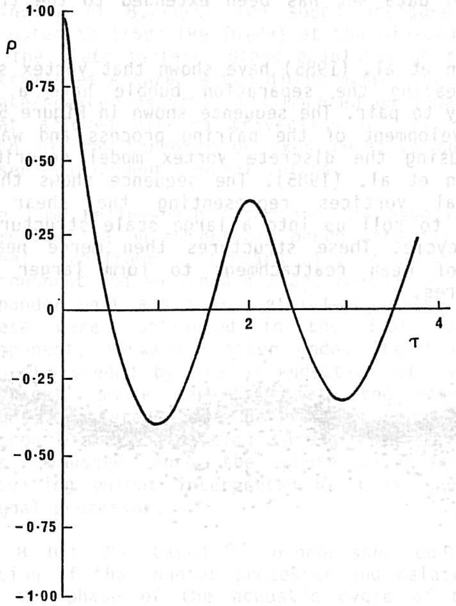

Fig 8: Autocorrelation from hot wire data measured at mid chord: ρ normalised coefficient, τ non-dimensional time (time/acoustic cycle)

CONCLUSIONS

The work has shown that LDA, in conjunction with conditional sampling, can be used to determine flow velocities in the region of the leading edge separation bubble when the flow is perturbed by an acoustic velocity field. The high degree of repeatability of measurement using LDA gives confidence in the method of measurement. It has confirmed previous experimental and numerical findings that the applied acoustic velocity perturbations regulate the shedding mechanism to form coherent patterns. Two major extensions to the work are the examination of alternative presentations of the data and the completion of measurements to the trailing edge of the plate. The latter will require accurate determination of the pairing structures and their relationship to the acoustic cycle. Both surface pressure measurement and hot-wire probes have been used to detect pairing and a combination of one of the methods with the existing acoustic phase counter is being investigated.

REFERENCES

Cantwell, B; Coles, D (1983): An experimental study of entrainment and transport in the turbulent near wake of a circular cylinder. J.Fluid Mech., vol.136, 321-374.

Hourigan, K; Welsh, M C; Welch, L W (1985): Augmented forced convection around a heated flat plate. ASME/AICHE National Heat Transfer Conference, Denver, USA.

Kiya, M; Sasaki, K (1985): Structure of large-scale vortices and reverse flow in the reattaching zone of a turbulent separation bubble. J.Fluid Mech., vol.154, 463-491.

Ota, T; Itasaka, M (1976): A separated flow on a blunt flat plate. J.Fluids Eng., vol.98, 79-86.

Parker, R; Welsh, M C (1983): Effects of sound on separated flow from a blunt flat plate. Int.J.Heat and Fluid Flow, vol.4, 113-128.

Perry, A E; Chong, M S; Lim, T T (1982): The vortex shedding process behind two dimensional bluff bodies. J.Fluid Mechanics., vol.116, 77-90.