Flow around an impulsively arrested circular cylinder

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Introduction

The case of an impulsively *started* flow around a circular cylinder has been studied long ago (e.g., Prandtl 1927) and has been used extensively as a benchmark for numerical validation. The periodic acceleration and arresting of flows during oscillations has been found to produce a variety of wake structures (Ongoren and Rockwell 1988; Williamson and Roshko 1988; Blackburn *et al*. 2001). However, little has been published on the isolated case of an impulsively *arrested* circular cylinder.

We have undertaken research recently on the flow related to the sudden arrest of a sphere due to impact on a wall (Leweke *et al.* 2004). In a parallel study, it was found that when the sphere was stopped away from the wall, the near-wake continued to self propel past the sphere for significant distances. In the case of a circular cylinder stopped in mid fluid, it may have been expected therefore that the wake would similarly flow around the cylinder and continue in the longitudinal direction.

A surprisingly different phenomenon however is observed. For both short and long running distances of the cylinder before arrest, the wake vortices, upon reaching the cylinder, are found to convect with significant lateral motion. For short running distances, two vortex pairs are formed that self propel laterally away from the cylinder and can even head back upstream at higher Reynolds number. For a long running distance, the Kármán wake vortices successively roll up on each side of the cylinder to form two larger structures.

Experimental Method

The experiments on the stopping-cylinder flow were carried out in a glass water tank of dimensions 50 × 50 × 60 cm^3. A schematic of the setup used is shown in Fig. 1. The cylinder was made of stainless steel; it has a diameter D = 6.0 mm, and a length of 300 mm, giving an aspect ratio of 50. It was fitted on one end with a circular plastic end plate of diameter 25 mm (~4D), the other end was free, in order allow visual access to the observation plane. The cylinder was attached to two inelastic strings (0.2 mm diameter), holding it in a horizontal position. The tow lines traversed near-frictionless pulleys above the water tank and were wound onto a metal spool with two helical grooves. The spool could be rotated by a stepper motor with a resolution of 50,800 steps per revolution. This allowed a very precise control of the vertical motion imposed on the cylinder. Temperature measurements were made to ensure that accurate estimations of the kinematic viscosity of the water and the Reynolds number were made.

For a given experiment, the cylinder is impulsively started from rest at its initial position near the water surface, guaranteeing an initial flow condition which is uniform in the axial direction, corresponding to two-dimensional flow. It traverses at constant speed U a distance of either approx. 10D (short running length) or 58–67D (long running length), which corresponds to approximately 10 vortex shedding cycles of the asymptotic flow at the Reynolds numbers considered here. For the short running length, the distance was short enough that two counter rotating vortices formed behind the cylinder but were not shed. For the long running length, the distance was long enough for the full development of the vortex shedding. At the same time it was also short enough to avoid the build-up of flow-induced transverse oscillations of the cylinder, as well as the contamination of the observation area in the centre of the cylinder by three-dimensional or end effects.

Visualisation is achieved by coating the central part of the cylinder outside the water with fluorescent dye (aqueous solution of Fluorescein).

Computational Method

An inhouse spectral element code was employed. The code has been used for a variety of problems including the predictions of 3D transitions wake modes in the wake of a circular cylinder (Thompson *et al*. 1996), in the wakes of rings (Sheard *et al.* 2003). The spectral-element method is a higher-order finite-element approach. For each element the node points lie at the quadrature points of a particular Gauss quadrature formula. In this case, the nodes correspond to Gauss-Lobatto points and Gauss-Legendre-Lobatto quadrature is used to approximate the integrations over elements resulting from the application of the Galerkin weighted residual method to the Navier-Stokes equations.

This method used is similar to that used by Tan *et al.* (2004) when studying vortex shedding and interactions in flows around flat plates and more details can be found there. After mapping the elements to a computational square, the spectral element technique uses the tensor product of high-order Lagrangian polynomials to interpolate the solution variables in each direction in each element.

The implementation is also second-order accurate in time through the application of higher-order pressure boundary conditions as described in Karniadakis, Israeli and Orzsag (1991). This temporal convergence has been verified through various tests for past applications.

The Reynolds number (*Re*) of the flow is based on the cylinder diameter (*D*) and velocity (*U*), and on the kinematic viscosity (ν) of the water at the measured temperature. Time t is counted from the instant the cylinder is stopped, and it is non-dimensionalised by the time it takes the cylinder to travel one diameter: $t^* = tU / D$.

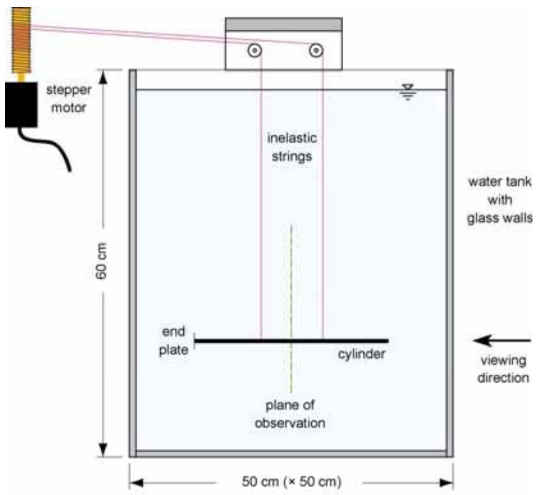


Figure 1. Schematic of the experimental setup.

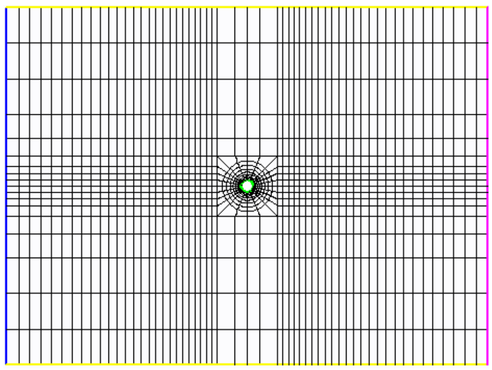


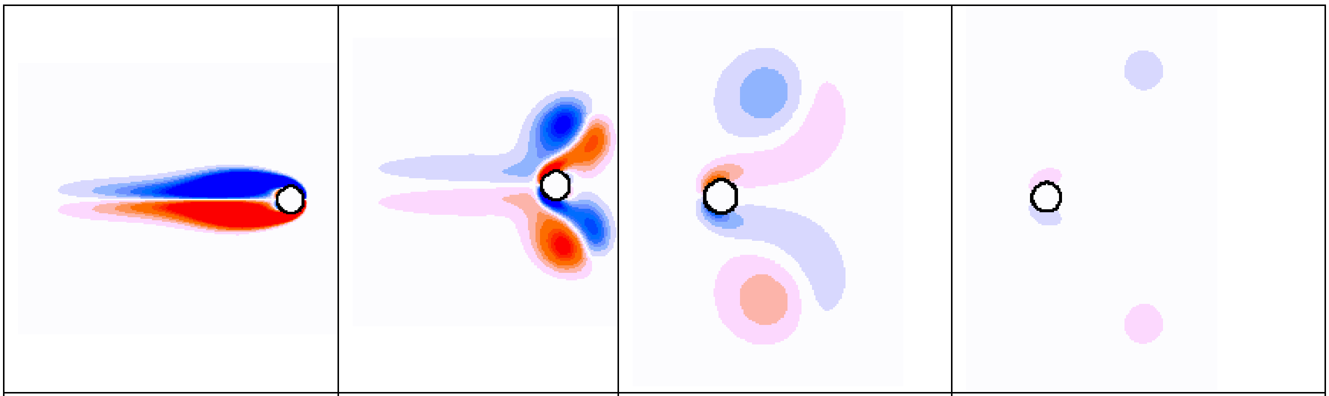
Figure 2. Macro elements of the mesh used for the case of an isolated cylinder in a flow where the flow stops after vortex shedding.

Results and Discussion

Short Running Length

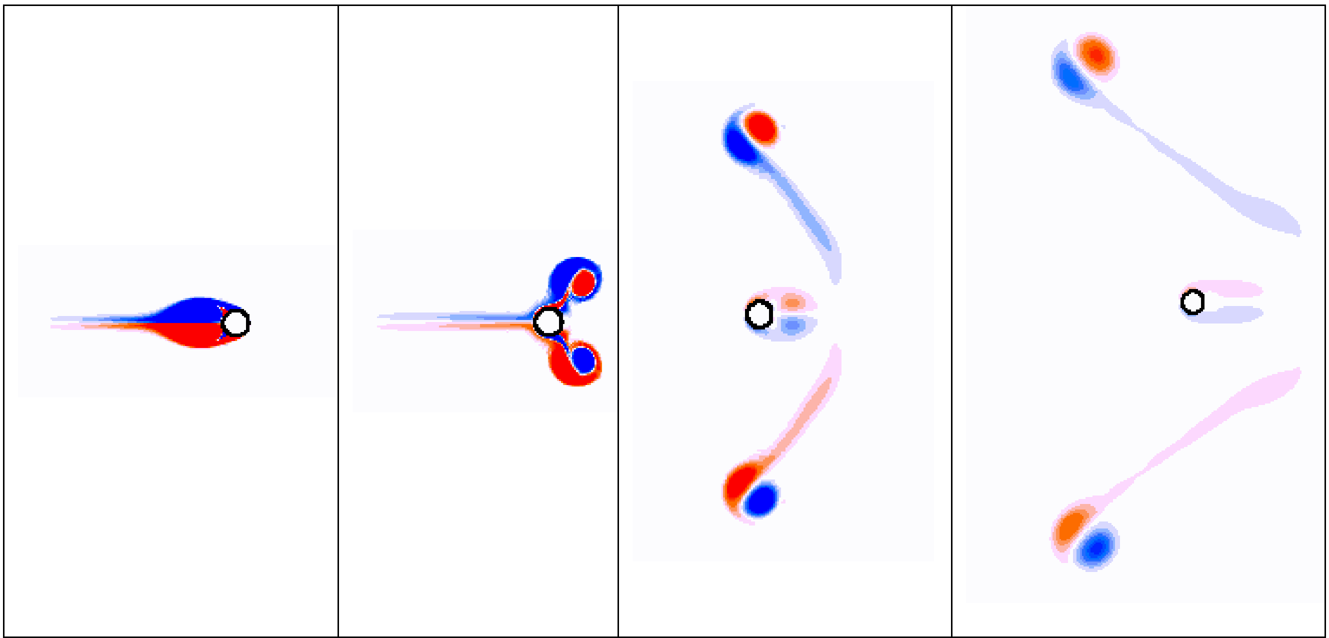
The trajectory of the wake vorticity following cylinder arrest is found to be dependent on the Reynolds number. The two cases of $Re = 100$ and 500 are presented here (Figs. 3 and 4) with a running length before arrest of 10 cylinder diameters. For $Re = 100$, the counter-rotating vortices of the wake separate as they pass over the cylinder. Secondary vorticity is generated on each side of the cylinder surface, with concentration in two regions; one draws away from the cylinder to form an unequal vortex pair with the primary vortex, the other remains near the cylinder surface. The vortex pair self-propels at approximately 45° to the longitudinal axis, with the secondary vortex dissipating to leave the decaying primary vortex about 5 cylinder diameters away from the cylinder and secondary vorticity at the cylinder surface.

The case of $Re = 500$ is more dramatic. In this case, a more distinct and persisting vortex pair is formed on each side of the cylinder. The pairs initially move obliquely outwards as for the lower-*Re* case, but then move in a predominantly lateral direction with a small component in the reverse longitudinal direction. The pair continues to self-propel far away from the cylinder. A distinct vortex pair formed from the counter-rotating secondary vorticity flowing from the cylinder remains.



a) $t^* = 0$ | b) $t^* = 10$ | c) $t^* = 30$ | d) $t^* = 70$

Figure 3. Predicted vorticity plots for an arrested cylinder at *Re* = 100 and short running length. Cylinder stops at $t = 0$.



a) $t^* = 0$ | b) $t^* = 5$ | c) $t^* = 20$ | d) $t^* = 70$

Figure 4. Predicted vorticity plots for an arrested cylinder at *Re* = 500 and short running length. Cylinder stops at $t = 0$.

Long Running Length

In the case of a long running length (i.e., approx. 60 cylinder diameters with a Kármán street having been formed before cylinder arrest), the flow is quite different. Instead of a symmetric pair of vortices only, there is a street of asymmetrically placed vortices that continue to drift towards the stopped cylinder. The subsequent wake development is more complex and is partly a function of the phase of the vortex shedding cycle at which the cylinder was arrested. Nevertheless, the common feature is that alternate vortices in the wake translate predominantly in the lateral direction upon reaching the cylinder (see the observations in Fig. 5 (*Re* = 75) and the predictions in Fig. 6 (*Re* = 100)). Eventually, the vortices from each side of the original vortex street roll up to form two larger vortices on each side of the cylinder which drift slowly forward.

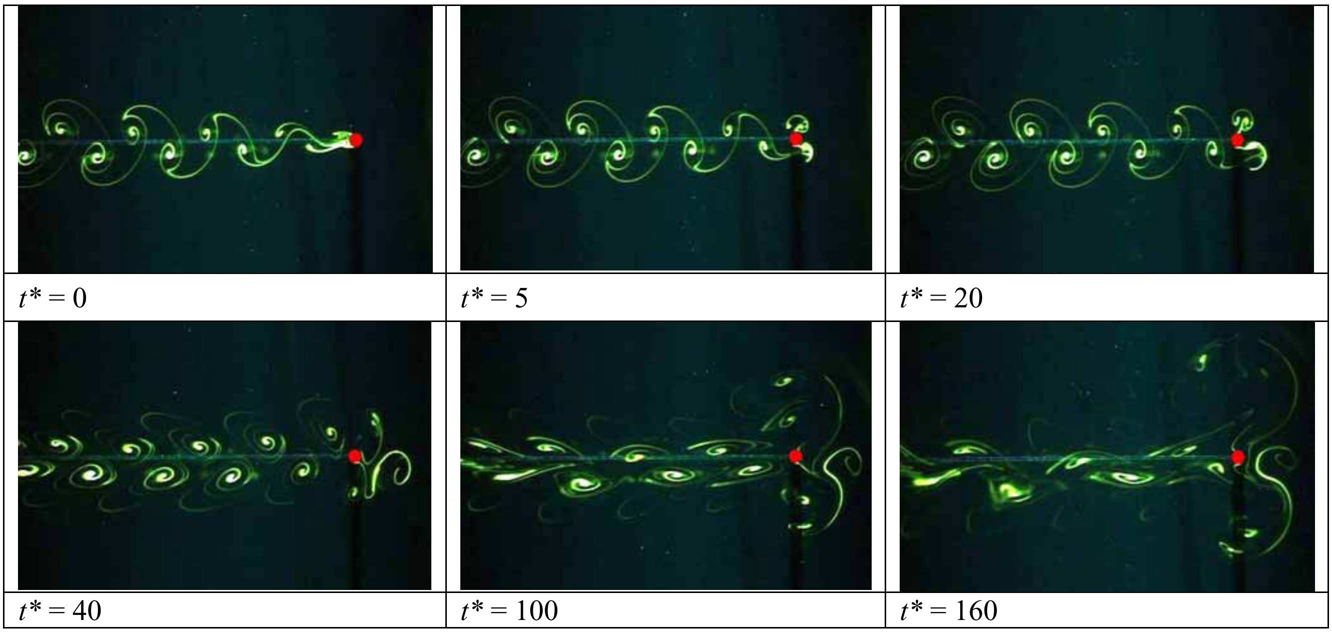


Figure 5. Sequence of observed visualisations for Re = 75.

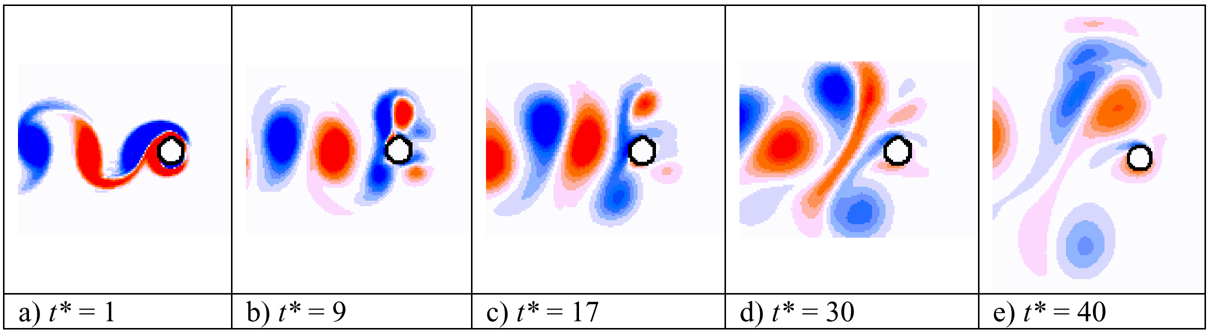


Figure 6. Predicted vorticity contours after the cylinder has stopped for Re = 100.

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