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THE INTERACTION OF A CYLINDER WAKE AND A FREE-SURFACE

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ABSTRACT

Results are presented showing the vortex structures in the wake of a cylinder placed in close proximity to a free surface. The case in which the cylinder is semi-submerged is discussed in detail; comparisons are made with previously-published results in which the cylinder oscillates or is static but placed just under the surface.

INTRODUCTION

Flow over circular cylinders has been studied extensively and yet continues to provide challenges, both to experimentalists and numericists. Recent advances in numerical algorithms, computational power and experimental techniques have resulted in new insights which have wide implications in the fields of bluff-body flows, transition, stability and nonlinear dynamics. Added to this is the importance of transport phenomena in flow over cylindrical elements of technological devices. Recent comprehensive reviews of the field have been provided by Williamson (1996) and Zdravkovich (1997)

An important field of application of the results from these studies is the static and dynamic loading of offshore structures. Here, there is often the added complexity of free surface effects. The flow over the body may also have a more complex form e.g. oscillatory or a freestream combined with transverse oscillations. A primary consideration is the force experienced by such bodies. These forces depend on a number of factors, one of which is the nature of the vorticity field surrounding the body – these vortices having been previously shed from the body. This work has always been of fundamental interest to researchers and practical concern to engineers. Both communities have had the benefit of particularly lucid reviews by Graham (1979), Bearman (1984) and Sarpkaya (1979). Recently, the advances in numerical and experimental techniques has provided instantaneous, time-dependent vorticity field data from which forces can be predicted and compared with matching, measured instantaneous force data, e.g. Lin and Rockwell (1997).

The work discussed here is part of an ongoing collaboration between Lehigh University and Monash University in Australia. The data presented forms part of a more extensive set, some of which has appeared elsewhere.

This paper primarily considers flow over a semisubmerged cylinder at low Froude number. However, because it is in part an attempt to review the Lehigh-Monash collaborative work, it contrasts this with the high Froude number case, the case in which the cylinder is undergoing forced, transverse oscillations, and the case of flow over a fully-submerged cylinder in which there is still an influence from free surface

PREVIOUS WORK

The work described was originally stimulated by the analytical and numerical study of Triantafyllou and Dimas (1989). They studied flow over semisubmerged cylinders with the aim of better understanding the stability of that case. They found that at low Froude numbers such flows were convectively unstable. The nature of the flow, which contains a "half saddle point" is intriguing and particularly rich in flow structures. Figure 1 shows the essential features of the flow: the cylinder is half submerged relative to the mean free surface level and a current flows over it. Vortices are shed from the side of the cylinder in the water and must ultimately interact with the free surface at a point downstream.

Analogous work exists for flow over cylinders with a splitter plate, as discussed for example by Kourta et al. (1987). In that case the solid boundary on the wake centreline also has an effect on both the Kármán and shear layer (Kelvin-Helmholtz) vortices.

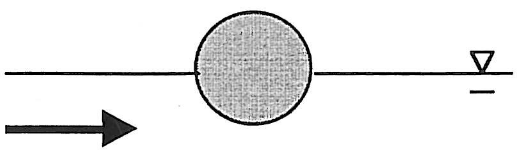

Figure 1 Schematic showing the cylinder sitting on the free surface in a current.

The work is also of interest because of the wide variety of related work of fundamental interest. An abbreviated list is presented below.

- The generation of vorticity at a free surface, as discussed recently, for example, by Rood (1995) and Hornung (1992).
- Reattachment in separated flows e.g. the backward facing step – Eaton and Johnson (1980).
- The influence on the free surface profile of vortices, both in stimulating breaking waves and in causing distortions, as per Ohring and Lugt (1992) or Yu and Trygvarsson.
- The passage of vortices, or vortex pairs, close to a free surface, as discussed for example by Bernal and Kwon (1989).
- At higher Froude number, the generation and downstream evolution of vorticity in hydraulic jumps or bores, as recently discussed by Hornung, Willert and Stuart (1995).

EXPERIMENTAL METHOD

All the results described were obtained in a free surface water channel at Lehigh University. The channel is 210mm wide and for the experiments described the water was held at a mean level of 527mm. The cylinder used was made from perspex and was 25.4mm in diameter.

Instantaneous velocities were measured using the high-image-density particle image velocimetry (PIV) system described by Rockwell et al. (1993). A (20W) continuous wavelength argon-ion laser beam was directed through the channel working section via a rotating mirror having 72 facets. This results in multiple exposures of particles in the channel in the period during which the camera shutter is open. Metallic-coated hollow spheres of 12 μm diameter were used to seed the flow. At a shutter speed of 1/250s three or four images were recorded per particle. Images were interrogated using a single-frame cross-correlation technique. The final grid-scale resolution of velocity vectors was 2.2 × 2.2 mm in experimental space. Due to flow reversals and the need to increase dynamic range, a rotating bias mirror was placed in front of the cameras lens; this imparts a constant bias velocity on the calculated velocity vectors.

For the semi-submerged cylinder the Froude number was varied between 0.25 and 1.75, being equivalent to a Reynolds number range of 2,230 – 15,380.

RESULTS AND DISCUSSION

Semi-submerged cylinder

Ensemble-Averaged results

Ensemble averaged PIV results for flow over the cylinder at the lowest Froude number tested, Fr=0.25, showed a long shear layer, which appears to have relatively little concentrated vorticity. Concentrations, indicative of Kelvin-Helmholtz vortices, would be present in the infinite fluid case at these Reynolds numbers. There is no apparent reattachment point in the field of view. There is, however, an initially-formed vortex some way downstream. Individual images making up the average showed considerable variation in this formation length. The shear layer does not appear to spread significantly after this vortex has formed, presumably because such spreading results from large scale vortex interactions, as discussed by Brown and Roshko (1974), and in this case the individual vortices form and convect downstream in isolation from the neighboring ones.

At higher Froude numbers the initially-formed vortex moves closer to the cylinder. For example, even at Fr=0.32 the vortex formation length has shortened and the shear layer clearly contains Kelvin-Helmholtz vortices. It is also at less of an angle to the free stream than in the Fr=0.25 case. Reattachment to the free surface appears to occur just out of the experimental field of view, but again this varies significantly between instances making up the average.

At higher Froude numbers the vortex formation length appears to be reasonably constant. However, the vorticity emanating from the cylinder is considerably stronger and there is greater spreading downstream of the formation point as a result. The spreading (or vortex attraction to the free surface) results in the vorticity from the shear layer interacting with the free surface not far downstream of the formation point. However, the strength of the vortices is not great enough to cause any observable distortion of the free surface Froude numbers less than 0.8. (There is, however, a drop in the free surface directly behind the cylinder.) At the higher Froude numbers there is clearly a reattachment point in the ensemble-averaged case but there may not be for instantaneous images

There is also entrainment upstream, often at a reasonable velocity. In observing the experiments the line of reattachment was seen to move unsteadily with significant backflow within the reattachment zone. There also appeared to be some three-dimensionality in this region, giving the impression of some type of cellular structure with a spanwise wavelength of the order of the cylinder's diameter. Three dimensionality could also be observed downstream of the reattachment point, but the two forms appeared to be different; this is not surprising given the different velocities involved. No detailed study was undertaken of the three-dimensionality of the vortices however.

At Fr ≥ 1 the free surface, having been drawn down directly behind the cylinder by the wake region, recovers its full elevation some distance downstream. This is similar to an hydraulic jump with the effect becoming more pronounced at higher Froude numbers.

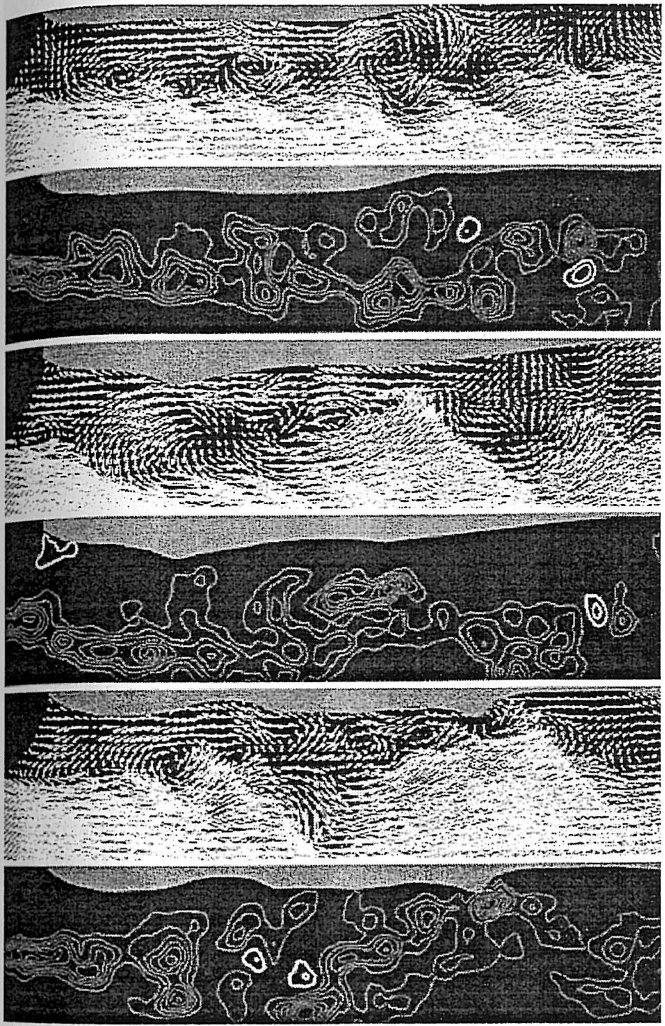

Figure 2. Instantaneous velocity and vorticity field distributions at Fr = 1.02. The three images are all taken at this Fr but at different instants: t_1 = top; t_2 = middle; t_3 = bottom.

Variation in Instantaneous Results

A characteristic of the semi-submerged cylinder flow was the high degree of variability it exhibited at the same condition i.e. Froude number.

The variability in the formation length is clearly evident in Fig. 2. This figure shows three instances of the flow, all taken at a Froude number of 1.02. At t_1 no formed vortex exists with all the vorticity again contained in the distinct shear layer leaving the cylinder. This contrasts with t_2 and t_3 in which a vortex has formed close to the rear of the cylinder. Compared to the equivalent ensemble average in Fig. 2(a) the formation length is short. This variability in formation length means that the cylinder will experience wider fluctuations in the force resulting from the vortices, which clearly has consequences for the dynamic loading experienced by the cylinder.

As can be seen at t_2, when a large vortex forms the swirling velocity field induces a large upstream flow, often extending some distance downstream of the cylinder. This flow brings with it the possibility of generating vorticity of the opposite sign, either on the free surface, if there is some curvature, or back at the cylinder. Examples of both mechanisms are evident at instant t_2. The small vortex near the free surface on the right of the frame appears to have been created by the interaction of the large shed vortex with the free surface in which it induces some depression in the surface and a tangential component of velocity, the prerequisites for free surface vorticity generation, as discussed by Batchelor (1967) and Rood (1995). On reaching the cylinder the flow is deflected up towards the free surface causing a vortex of opposite sign to that of the shear layer to form on the back of the cylinder. While instances t_2 and t_3 are similar in forming a single, large, shed vortex the unsteady character of the flow can be seen in the differences in how the vortices form. At t_2 the vortex arises from an agglomeration of shear layer vortices while at t_3 the shear layer is very short and the large, more distinct vortex appears to have been shed very close to the cylinder. Again, the formation of the large vortex has an effect on the angle of the shear layer to the free stream, as illustrated in the relatively large angle at t_2.

The reattachment length is difficult to define in these cases. Some attempts were made to resolve this issue by seeking to define some objective criterion with which to define x_R. However, no satisfactory criterion was found. Large vortices induce their own local reattachment, as shown at t_2 where there is a local change in the flow direction at the free surface on the downstream side of the initially formed vortex. Thus, the arguments concerning reattachment length advanced by Triantafyllou and Dimas (1989) could not be resolved because of the unsteadiness in the flow. It is, however, apparent that the reattachment length shortens with increasing Froude number, as does the formation length. Interestingly, the application of PIV to flows such as this and the backward facing step are forcing a re-evaluation of concepts such as reattachment length (Eaton and Johnston (1980) offer a particularly clear discussion of such issues).

Free Surface - Vortex Interaction

Previous studies, such as those of Weigand and Gharib (1994) and Bernal and Kwon (1989), have investigated the passage of vortex pairs towards free surfaces, however, even at the lowest Froude number used in this study the flow appears too disturbed to observe the interaction of a single vortex with the free surface at their level of detail.

There were cases, as shown in Fig. 2, where vortices appeared attracted to the free surface. This resulted in the shear layer also being drawn towards the free surface. In other cases the formed vortex was convected along at some depth under the free surface. The angle the shear layer makes to the free surface appears to depend on which of these paths the vortex takes.

Instant t_3 shows a case where the vortex has been attracted to the free surface, in this case consistent with the uppermost vortex in the study of Bernal and Kwon (1989). The pattern of vorticity shown here was often observed in processed images and in the flow channel. In the image it appears that the vorticity in the shear layer is drawn up into contact with the free surface but immediately detaches from it downstream of this point. The shear layer then is angled down into the fluid often reaching a considerable depth.

This "looping" of this shear layer can generate vorticity of opposite sign at the free surface. This vorticity was presumably caused by the free surface deformation and tangential velocity induced by the vortex. This generation of opposite signed vorticity by the approach of a vortex to a free surface is shown, for example, in the numerical and analytical studies of Lugt and Ohring (1991).

Free Surface Deformation

At the higher Froude numbers the vortices shed from the cylinder interact with the free surface as described above but, because of the higher levels of vorticity, they can now noticeably deform the free surface. This can take place in several ways. Fig. 2 shows free surface deformation resulting directly from the presence of a vortex. At the higher Froude number of 1.75, shown in Fig. 3, there is considerably more deformation in the free surface, in this case taking the form of an hydraulic jump.

At the highest Froude number shown of Fr=1.75, the flow bears a strong resemblance to a breaking wave of the form discussed in detail by Lin and Rockwell (1995). As in their case, the toe of the breaker is a region of significant vorticity which has a shear layer attached to it which is angled down into the fluid. In their case, however, this toe region appears to be a source of vorticity whereas in the present case it is difficult to discern whether the vorticity emanates from the free surface or is that originally present in the shear layer.

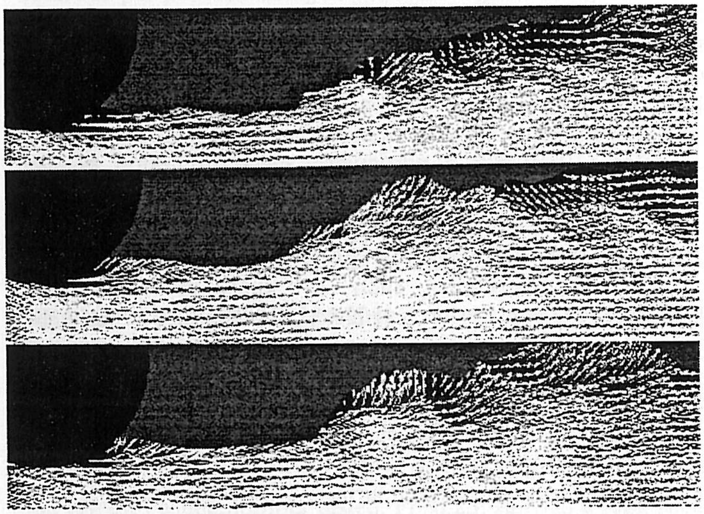

Figure 3 Flow over a semi-submerged cylinder at Fr = 1.75 for three separate instants

Oscillating semi-submerged cylinder

Lin et al. (1996) investigated the semi-submerged cylinder subject to transverse oscillations. This flow is of considerable interest because it replicates, albeit in an idealized form, the passage of wave-like disturbances in such cases. It is also interesting in the light of the current interest in flows over transversely oscillating cylinders in infinite fluids.

Their results indicate that the vortex shedding locks to the applied perturbation over a wide range of frequencies around the natural vortex shedding frequency. Perturbation amplitudes as low as A/D = 0.08 appeared sufficient to phase-lock the vortex formation.

These results are interesting in the light of Triantafyllou and Dimas (1989) stability analysis, where it was found that the near wake should be convectively unstable. This would imply that the wake would be responsive to applied perturbations.

Also of interest was the approach of the initially-formed vortex to the rear of the cylinder at the natural vortex shedding frequency. This is consistent with the results of Gu et al. (1994), where the effect on the energy exchange between the fluid and the body is discussed..

Submerged Cylinder

A problem bearing many similarities to the above is the case where the cylinder is placed under the free surface but close enough for the wake to be influenced by it.

Figure 4 shows such a flow. In this case the Froude number, based on cylinder diameter, was 0.6 and the top of the cylinder was placed 0.3D below the mean water line.

Sheridan, Lin and Rockwell (1997) have discussed the rich variety of flow states that can be found in such a flow. The particular case shown in Fig.4 where, for effectively the same set of experimental conditions, strikingly different flows result, has been discussed in more depth by Sheridan, Lin and Rockwell (1996).

Of particular interest in this case is the separation of the flow from the free surface in the case where the jet issues down into the fluid (bottom figure). The vorticity generated at the cylinder and free surface match and form Kelvin-Helmholtz vortices on the two sides of the jet. In the top image, which is generally found at greater depths than the bottom case, the flow remains attached to the free surface. When this occurs the distortion of the free surface is much greater, taking the form of a standing wave directly behind the cylinder. In some cases this wave exhibits the characteristics of a spilling breaker and has many features in common with the breaking waves investigated by Lin and Rockwell (1995)

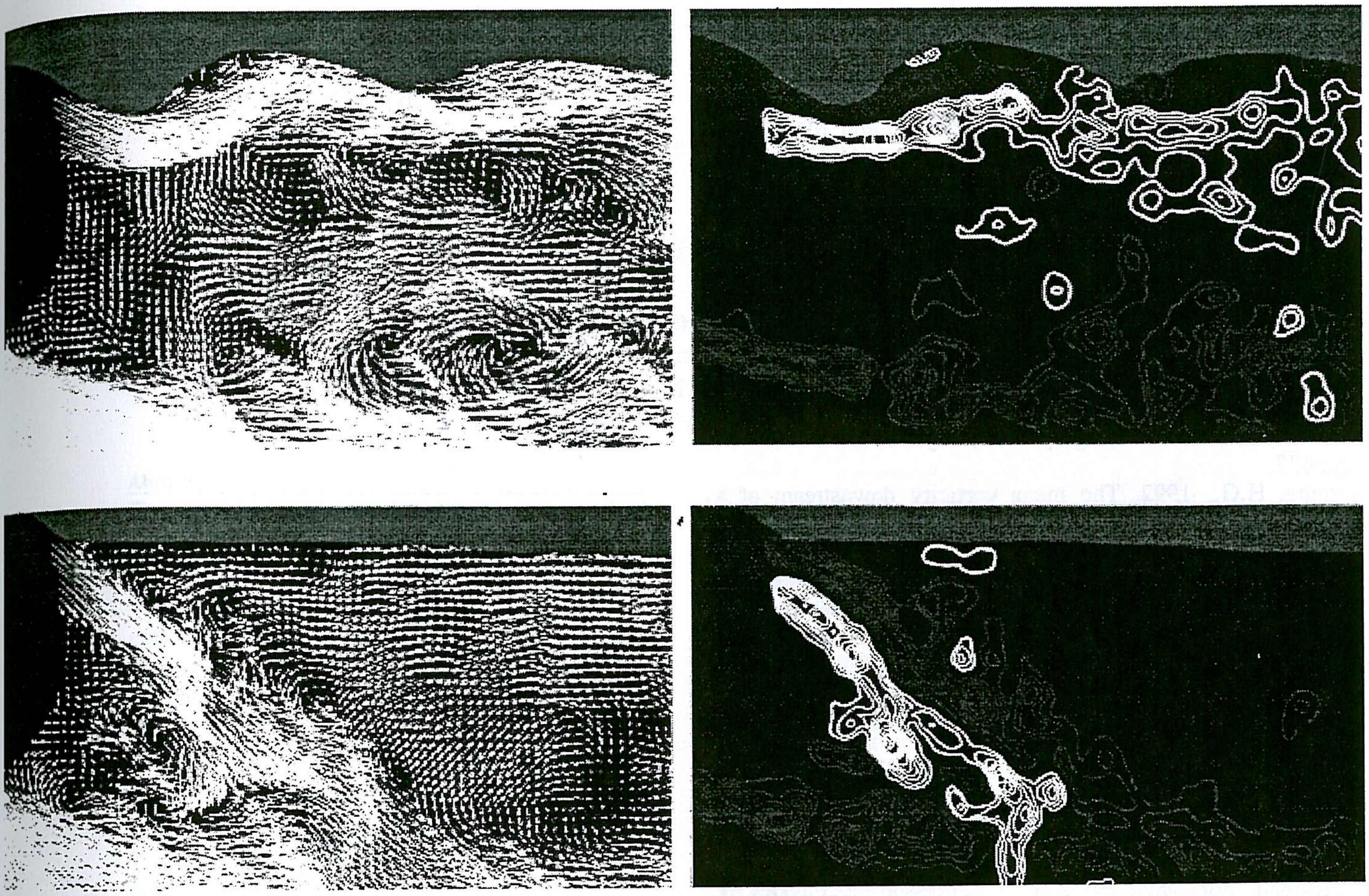

Figure 4. Flow over a cylinder placed under a free surface. Both cases are for Fr=0.6 but were taken at different instants. Velocity fields on the left and vorticity fields on the right.

CONCLUSIONS

A summary has been presented of some recent experimental studies aimed at elucidating the flow structures in cylinder wakes and how they interact with free surfaces close to them.

Cases considered were:

1. Flow over a semi-submerged cylinder at Froude numbers between 0.25 and 1.75.
2. Flow over a semisubmerged cylinder which is being oscillated transverse to the flow.
3. Flow over a cylinder placed just under a free surface.

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