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# FLOW PAST A CYLINDER SUBMERGED UNDER A FREE SURFACE

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## ABSTRACT

Flow past a cylinder close to a free surface is examined numerically using a finite volume method. The preliminary results for Froude number 0.60 and submergence depths of 0.00, 0.25 and 0.75 diameters are presented. This range of parameters was chosen so as to cover a number of different wake states. These results are then compared with experimental results of Sheridan *et al.* (1997).

## INTRODUCTION

Flow past a fully submerged circular cylinder may be considered as a classical problem of fluid mechanics; as such it has received a substantial amount of attention. However, the related problem of flow past a cylinder close to a free surface has received little consideration until recently in spite of its numerous applications in the field of marine engineering and tank agitation.

A detailed experimental investigation on the topic, was first considered by Sheridan *et al.* (1997), in which they describe a spectrum of behaviour which differs greatly from that of the more classical fully submerged case. They note in particular that the free surface signature and the corresponding wake behaviour are essentially dependent on two parameters, these being the Froude number $Fr$ (where $Fr = u/\sqrt{dg}$) and the depth of submergence $h$ (see figure 1 for the definitions). The type and stability of this behaviour is then classified for various $Fr$ and $h$ values, and the degree of sensitivity to these parameters is noted. The wake structures observed by Sheridan *et al.* (1997), could then be loosely categorised depending upon the position of the "jet" (jet of fluid which passes over the cylinder), i.e., whether it was attached to the cylinder, the free surface, or somewhere in between. Warburton and Karniadakis (1997) have since investigated a subset of the behaviour of Sheridan *et al.* (1997) using a 2D spectral element technique with a free surface modelling capability. They reported a general agreement with the experiments, and hence it may be suggested that the dominant characteristics of this system are primarily two-dimensional in nature.

Another case of interest includes the interaction of a cylinder with solid surface, as considered by Bearman and Zdravkovich (1978), in which they found that shedding could be suppressed when the distance between the wall and the cylinder was less than 0.3 cylinder diameters.

For the problem of interaction of vortices with a free surface, Yu and Tryggvasson (1990), and Ohring and Lugt (1991), found that the interaction can be classified by essentially two limits depending on Froude number. (In these cases the Froude number is based on vortex, not mean flow, speed). They report that in the low Froude number limit, the vortices interact with the surface as if it were a solid wall, while for the high Froude number case the vortices cause substantial surface deformation.

With regard to the nature of the instabilities observed by Sheridan *et al.* (1997), the paper by Triantafyllou and Dimas (1989) provides some insight. They consider the case of a floating half-submerged cylinder. As a result of their analysis they note that the flow is convectively unstable for Froude numbers (based on radius) less than approximately 2.5, but that it is absolutely unstable for larger Froude numbers.

Dimas and Triantafyllou (1994) also numerically investigated the non-linear interaction of shear flow with a free surface. In this invisid examination they re-iterate that the linear stability analysis of Triantafyllou and Dimas (1989) shows that two linear instability modes exist. These modes are then classified as either Branch I or Branch II modes, depending upon the value of the wave and Froude number. They conclude that Branch I instabilities develop significant horizontal but small vertical velocities at the free surface, while Branch II instabilities develop small horizontal but considerable vertical velocities.

### Present Study

The aim of the current study is to capture and identify some of the key types of behaviour observed by Sheridan *et al.* (1997). In particular the various cases involving the different positions of the 'jet' will be sought with a view to investigating the sources of vorticity production in future studies.

## NUMERICAL METHOD AND PROBLEM SETUP

The current study is performed with a commercially available code: CFX version 4.1. In order to model the free surface, which in practice is an interface between water and air, a two dimensional incompressible multi-phase finite volume scheme is employed. This model essentially calculates the flow field for a single phase (with variable density and diffusivity) and determines the degree of mixing between the phases via the void or volume fraction. The scheme used should produce results which are second-order accurate for velocity and pressure and first-order accurate for volume fraction. More details on this technique may be found in the CFX4 user manual.

The system setup simply involved two phase flow entering into the domain with a uniform velocity through the inlet and leaving though an outlet boundary where a pressure boundary condition is applied. The two phase inlet was set in such a way that below a certain height the flow was purely phase 1 whilst above that height it was purely phase 2 (If one considers phase 1 to be water and phase 2 to be air, then this is somewhat similar to the case of Sheridan *et al.* (1997)) The properties of the two phases were set as follows:

Density ratio

$$\frac{\rho_{phase1}}{\rho_{phase2}} = 100$$

Viscosity ratio

$$\frac{\nu_{phase1}}{\nu_{phase2}} = 1$$

A viscosity ratio of 1 was selected in these preliminary investigations, as larger differences made convergence more difficult. While such ratios are considerably different from the experimental case of Sheridan *et al.* (1997), it is expected that the results should be fairly insensitive to these ratios.

In order to model the effect of gravity, a body force was applied to each phase. However, it was found that when such forces were applied using the current model, that an undesirable degree of mixing of the two-phases occurred in the region just behind the cylinder. In order to overcome this problem, the body force on the lighter phase was set equal but opposite in direction to that on the heavier one. This resulted in the suppression of mixing and prevented the second phase overly influencing the cylinder wake development.

### Governing parameters

The governing parameters of the system were found by Sheridan *et al.* (1997) to be the dimensionless height $h^* = h/d$ (where $h$ is the depth of submergence and $d$ is the cylinder diameter), and the Froude number $Fr = u/\sqrt{dg}$ (where $u$ is the inlet velocity and $g$ is the gravitational constant). These are best illustrated in figure 1.

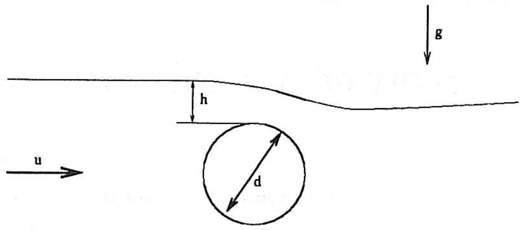

Figure 1: Schematic of the set-up.

In order to adjust the depth of submergence, the height at which phase 1 entered the domain was altered, this effectively allowed the value of $h^*$ to be set to within an accuracy of one grid cell (Maximum uncertainty in $h^*$ being 0.02). The Froude number was then set by fixing the value of $g$. The top and bottom boundaries of the domain were set to be free slip.

## RESULTS

For each of the cases described below, the Froude number was set to 0.60 and the dimensionless depth of submergence was varied between $h^* = 0.00$ and $h^* = 0.75$. The Reynolds number of the flow was 100. All results shown are steady state results; time dependent predictions will be considered in future investigations.

### Cases

$h^* = 0.00$

This result (figure 2) shows moderate agreement with the results of Sheridan *et al.* (1997). A region of reverse flow is predicted directly behind the cylinder, with a small amount of jetting associated with the upper stream, there is also noticeable flow along the surface. Sheridan *et al.* (1997) (figure 3), do not however, observe flow along the surface, athough they do note the region of reverse flow. Such discrepencies are likely due to there being only small amounts of flow over the cylinder.

$h^* = 0.25$

For this case, one can clearly see that the jet hugs the surface of the cylinder, displaying a Coanda like type of behaviour (figure 4). This result agrees well with that Sheridan *et al.* (1997) (figure 5), except with regard to the position of the free surface just behind the cylinder, with the numerical result predicting a higher surface elevation in this region. The general flow patterns also differ slightly from those in Figure 4, with the predicted behaviour showing flow along the surface while the experimental results do not.

$h^* = 0.75$

For this case, good agreement is noted between the numerical and experimental results (figures 6 and 7). The predicted wave on the surface and its position is consistent with the result of Sheridan *et al.* (1997). In addition a large region of distorted reverse flow is observed.

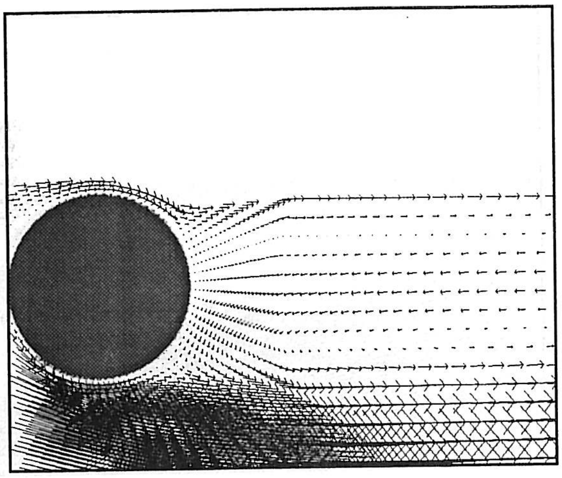

Figure 2: $h^* = 0.00$, $Fr = 0.60$

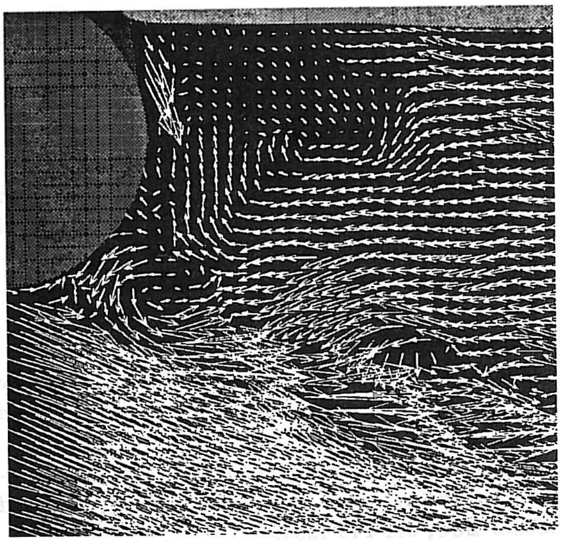

Figure 3: Results of Sheridan *et al.* (1997). For $h^* = 0.00$, $Fr = 0.60$ (Reproduced from the Journal of Fluid Mechanics, Vol 330, with permission)

For all of the above cases, there is that a general agreement between the experimental and numerical results. In particular some of the differing "jet" states observed by Sheridan *et al.* (1997) were detected, and the parameters at which such behaviour occurs also showed similarity. The major differences between the results concerned the actual position of the free surface, with the numerical results showing very little drop in the height of the surface just following the cylinder, which is in contrast to the experimental results. A possible explanation for this discrepancy is that current viscosity ratio will support shear at the free surface and hence the lighter phase will have the capacity to drag the heavier phase along, it is also possible that the use of a steady solver for this time dependant problem, may have resulted in the higher

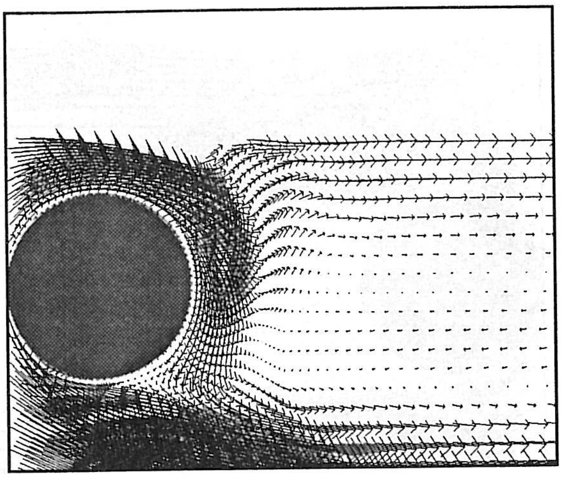

Figure 4: $h^* = 0.25$, $Fr = 0.60$

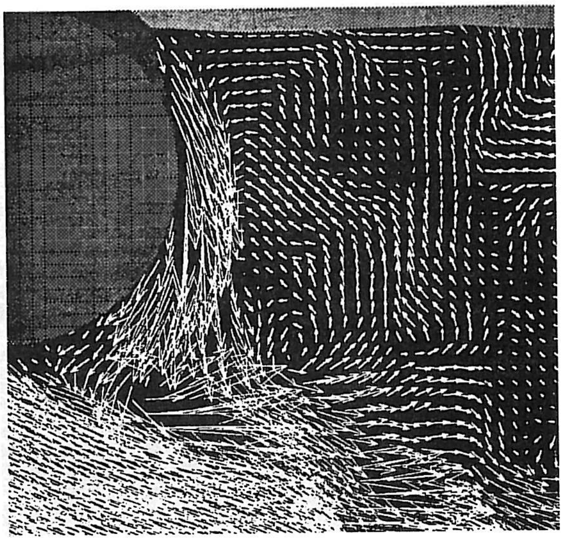

Figure 5: Results of Sheridan *et al.* (1997). For $h^* = 0.24$, $Fr = 0.60$ (Reproduced from the Journal of Fluid Mechanics, Vol 330, with permission)

predicted surface elevation. Another source of difference is the lower Reynolds numbers used in these predictions which affects the formation length and hence influences the wake structure formed; an effort is currently being made to increase the Reynolds number of the simulations.

For all of the cases examined the free surface was found to be relatively flat with only a slight amount of deformation being observed just behind the cylinder, which is largely in agreement with the experimental results for the values of $h^*$ and $Fr$ examined. What is interesting to note, and what is not shown in Sheridan *et al.* (1997) is the behaviour of the flow just upstream of the cylinder. For some cases the flow had a noticeable upstream influence extending up to 2 or 3 diameters. This was particularly the case

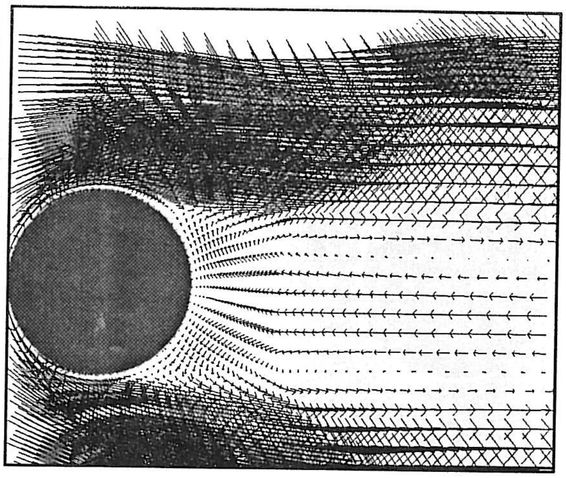

Figure 6: $h^* = 0.75$, $Fr = 0.60$

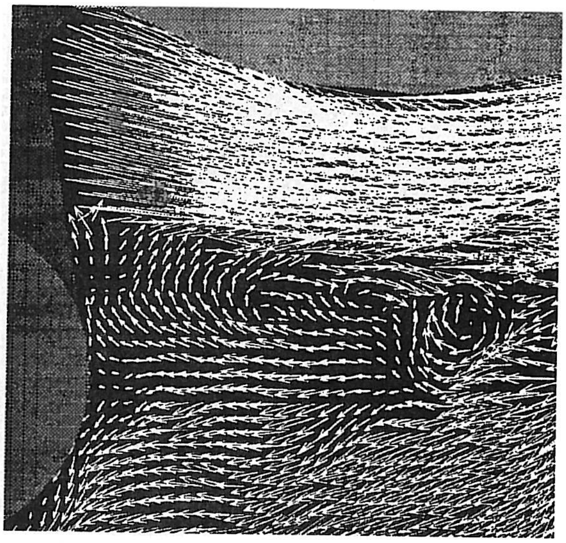

Figure 7: Results of Sheridan *et al.* (1997). For $h^* = 0.75$, $Fr = 0.60$ (Reproduced from the Journal of Fluid Mechanics, Vol 330, with permission)

for small submergence depths, where the flow was to some extent restricted from flowing over the cylinder, and hence had to adjust in order for it to flow under. This upstream influence is shown in figure 8.

## CONCLUSION

The prediction of the flow around a cylinder submerged close to a free surface is found to be well predicted using the finite volume code CFX. While some compromises involving density and viscosity differences between the two phases, and the Reynolds number of both phases had to be made to allow numerical convergence, the prediction of the main features, such as wake formation and the Coanda effect, over a range of submergence depths was possible. Future research will now concentrate on the details of

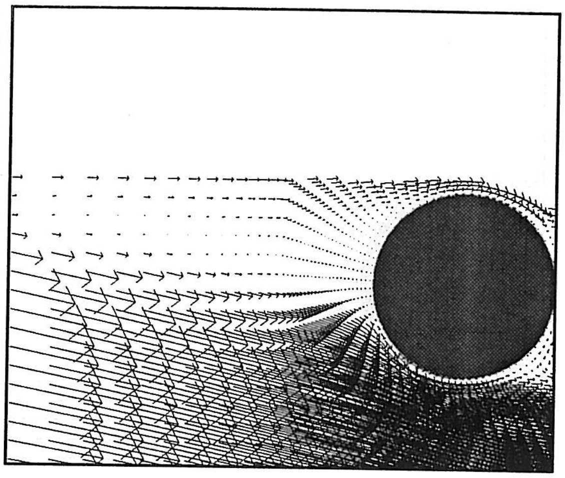

Figure 8: Upstream view for the case of $h^* = 0.00$, $Fr = 0.60$

the interaction between the wake vorticity and the vorticity generated at the free surface.

## ACKNOWLEDGEMENTS

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## REFERENCES

Bearman, P.W. and Zdravkovich, M.M., "Flow around a cylinder near a plane boundary" *J. Fluid Mech.* **89,** 33-47 1978.

Dimas, A.A. and Triantafyllou, G.S., "Nonlinear interaction of shear flow with a free surface" *J. Fluid Mech.* **260,** 211-246 1994.

Ohring, S. and Lugt, H.J., "Interaction of a viscour vortex pair with a free surface" *J. Fluid Mech.* **227,** 47-70 1991.

Sheridan, J., Lin, J.-C., and Rockwell, D., "Flow past a cylinder close to a free surface" *J. Fluid Mech.* **330,** 1-30 1997.

Triantafyllou, G.S. and Dimas, A.A, "Interaction of two dimensional separated flows with a free surface at low Froude numbers" *Physics of Fluids A* **1,** 1813-1821 1989.

Warburton, T.C. and Karniadakis, G.E., "Spectral simulations of flow past a cylinder close to a free-surface" *The 1997 ASME Fluids Engineering Division Summer Meeting,* Vancouver, Published on CDROM FEDSM 97-3389.

Yu, D. and Tryggvason, G., "The free surface signature of unsteady, two dimensional vortex flows" *J. Fluid Mech.* **218,** 547-572 1990.