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FLOW PAST A SHALLOWLY SUBMERGED CYLINDER

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ABSTRACT

In this research, the three dimensional flow around a cylinder placed near a free-surface is investigated at high Reynolds number using detached eddy simulation. The Karman-vortex shedding, force coefficients and velocity contour are observed at high Reynolds number, $3x10^6$. The wake behavior for Froude numbers 0.9 and for gap ratio 0.5 is examined. For low Froude numbers, where the surface deformation is minimal, the simulations reveal that this problem shares many features in common with flow past a cylinder close to a slip wall. At Froude numbers in excess of 0.3 – 0.4, surface deformation becomes substantial. This can be traced to increases in the local Froude number to unity or higher in the gap between the cylinder and the surface, resulting in localized free-surface sharpening and wave breaking. Since surface vorticity is directly related to surface curvature, such high surface deformation results in significant surface vorticity, which can diffuse and then convert into the main flow altering the development of Strouhal vortices from the top shear layer, affecting wake skewness and suppressing the absolute instability. A huge surface vorticity is experienced when the free-surface starts to break which affect the main stream vorticity.

Keywords: Karman-Vortex, Surface Vorticity, Wake Skewness.

1. INTRODUCTION

Flow past a cylinder close to a free surface has potential relevance to a large number of practical applications such as pipelines, offshore structures, submarines and power generation equipment using tidal power. While some attention has been focused on some parameter ranges, it has not yet been studied in detail. This contrasts with the related but simpler problem of flow past a cylinder in an infinite medium, which has been explored in depth over virtually all parameter ranges; by Morkovin [1], Berger & Wille [2] and Williamson [3]. Thus, perhaps a useful viewpoint is that the influence of the free-surface can be considered to cause changes from the infinite-medium reference case, although these deviations can, of course, be very large. In addition to the Reynolds number, $Re = \rho ud/\mu$, where u is the upstream velocity, d is the cylinder diameter, ρ is the density and μ is the molecular viscosity, the introduction of the free surface introduces two new parameters: the Froude number, $Fr = u/\sqrt{gd}$, where g is the gravitational acceleration; and the gap ratio *h/d*, with h the distance between the top of the cylinder and the position of the undisturbed surface. Dimas & Triantafyllou [4] later extended their investigations to examine the nonlinear interaction of a long wave length. Vortex shedding behind a circular cylinder has been the subject of a number of studies. Given a long circular cylinder with its axis perpendicular to fluid flow, the well known Karman-type (asymmetric) vortex shedding may occur behind the cylinder, the control or suppression of which is of great interest as it is closely related to various fluid-mechanical properties of practical importance, such as flow-induced forces, vibrations and noises, and the efficiencies of heat and mass transfer. There are several situations where this type of vortex shedding may cease, and one of them is when a free surface is located near the cylinder; the focus of the present study is on this flow configuration.

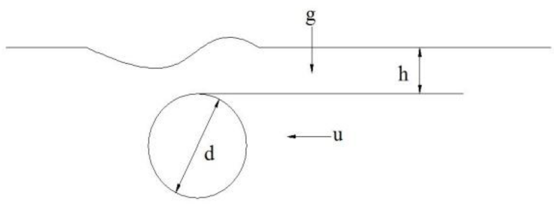

Fig 1. Schematic diagram showing the problem setup and important parameters

The characteristics of flow around a circular cylinder placed near and parallel to a ground are governed not only by the Reynolds number, *Re* but also by the gap ratio, i.e., the ratio of the gap between the cylinder and the free surface, *h*, to the cylinder diameter *d*. However, the mechanisms of the flow and force variations caused by different *h/d* or free surface effect. The numerical study reported in this paper is a subsequent study of the experiments described above. Flow around a circular cylinder, however, is still a very challenging subject in itself in today's computational fluid dynamics (CFD) even if the cylinder is outside the Free-surface effect; unsteady Reynolds-averaged Navier-Stokes (URANS) simulations cannot reproduce with sufficient accuracy the flow structures of wide-ranging spatial and time scales, whilst large-eddy simulations (LES) are possible but still quite expensive. Detached-Eddy Simulation (DES) is one of the novel approaches that combine the concepts of URANS and LES to obtain realistic solutions for practical high *Re* flows at acceptable computational cost.

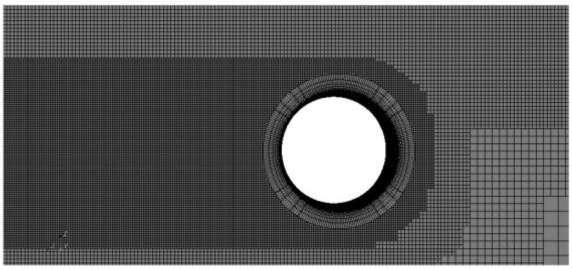

Fig 2. Computational grid

2. FLOW MODELING

The problem setup is shown in Figure 1, together with the important dimensions. The flow is from right to left with the cylinder submerged a distance *h* below the surface (under no flow conditions). The diameter of the cylinder is *d* and the upstream velocity is *u*. Since we have a free surface, the gravitational acceleration, *g* exerts an influence and must be considered. The important physical parameters are given in the introduction and are the Reynolds number, *Re* the Froude number, *Fr* and the gap ratio, *h/d*. In the limit, $Fr \rightarrow 0$, the surface becomes a non-deformable horizontal free-slip surface. The Strouhal number, $St = fu/d$, where *f* is the vortex shedding frequency in the wake is another important physical parameter characterizing the flow state.

2.1. Computational Details

Three-dimensional (3-D) DES simulations are performed on flow around a circular cylinder placed near and parallel to a free-surface. Figure 2 shows the computational domain. The boundary conditions are as follows-

Inlet = velocity inlet
Top = velocity inlet
Outlet = pressure outlet
Left = slip wall
Right = slip wall
Cylinder = No-slip condition

The free surface effect is simulated by a gap-ratio of 0.5 & a uniform flow velocity of 2.94 m/sec. The domain contains approximately 1.7 million cells. The Flow has a turbulence intensity of 2.48 % & a Reynolds number of $3\text{x}10^6$.

2.2. Numerical Method

The simulations are carried out using the computational fluid dynamics software package STAR CCM+. Only a brief description of points of direct relevance to the computations is provided here, further details of the implementation can be found in the STAR CCM+ Manuals. A description of the volume-of-fluid (VOF) method used to treat two-phase flows is given in Hirt & Nichols [5]. The main computational difficulty is the deformable free-surface. There are various ways to treat this situation numerically. A potential constraint in this case is that the surface may form breaking waves at high Froude numbers, which means that computational methods that track the surface directly as a computational boundary may have difficulties. It is decided to tackle the problem using the volume-of-fluid approach. Here, both the fluid phase and the much lighter gas phase above it are treated explicitly by introducing a (fluid) volume fraction, $\alpha 1$, and gas volume fraction, $\alpha 2$. The combined volume fraction of both phases must satisfy the conservation property, $\alpha 1 + \alpha 2 = 1$. A conservation equation is solved to transport the volume fraction of one of the phases. The viscosity and density at any point are obtained by volume phase averaging. A single momentum equation is solved for the whole domain resulting in a shared velocity field for both phases. The surface is defined to be the locus of points where $\alpha 1 = 0.5$. In practice, the surface is represented by piecewise linear segments across each cell.

2.3. Validation And Resolution Tests

To ensure that this mesh was fine enough to resolve the flow properly for the actual flow problem considered in this paper, a resolution study is undertaken. Physical parameters are determined for $Re = 1\text{x}10^6$, $h/d = 1$ and $Fr = 0.31$. The obtained results are validated with the results

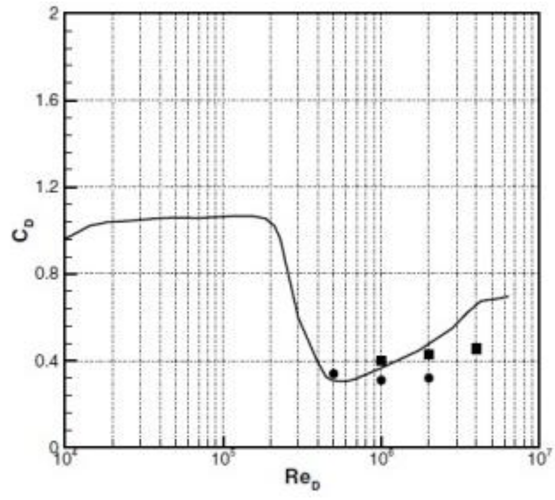

Fig 3. Drag coefficient as a function of the Reynolds number.

obtained by Pietro Catalano et al [6]. They found that the drag coefficient at high Reynolds number $1\text{x}10^6$ using LES numerical method is 0.31, using the RANS it is 0.39 and using URANS it is 0.40. In the experiment Zdravkvich [7] found the range of drag coefficient is

0.17-.40. In this study the drag coefficient using DES is .41 which is acceptable as it is a numerical solution so an error of 2.5%. In numerical simulation, time step of Δt = 0.002 sec according $U\Delta t = D/500$ and Re = $3x10^6$ is used. Achenbach [8] shows that the drag force is highly dependent on Reynolds number and according to his study the drag coefficient for a Reynolds number of $3x10^6$ is in the range of 0.7-0.8 and in this study the obtained drag coefficient 0.75.

2.4. Selection Of The Reynolds Number

The aim of this study is to perform fully three-dimensional DES at high Reynolds numbers; these would be extravagantly expensive and would certainly prohibit a parameter space study, which is a key aim of this research. To reproduce the main physical behavior and the effect of various parameters, three-dimensional simulations are performed high Reynolds number. The Reynolds number chosen for the bulk of the simulations is Re = $3x10^6$. As the flow past a ship or even an underwater vehicle like submarine those are very high speed is fully turbulent environment that's why DES at high Reynolds number is chosen.

3. RESULTS AND DISCUSSIONS

The surface vorticity field is quite strong & has suppressed the main stream vorticity field in the downward direction. Figure 4 to Figure 11 shows occurrence or non-occurrence of vortex shedding as a function of gap ratio. Triantafyllou & Dimas [4] showed that in the extreme case where the cylinder is only half submerged the wake instability changes from absolute to convectively unstable. This is consistent with suppression of vortex shedding when the cylinder is placed within close proximity to the surface. The effect of Froude number on the wake dynamics and surface distortion is investigated at Froude number of 0.90 & gap

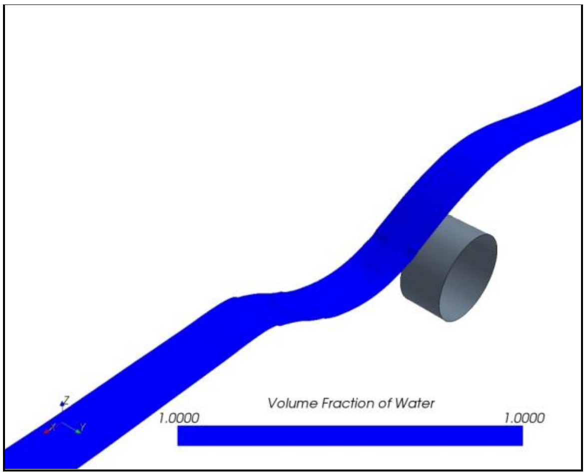

Fig 4. Free surface development at time=1.092 sec

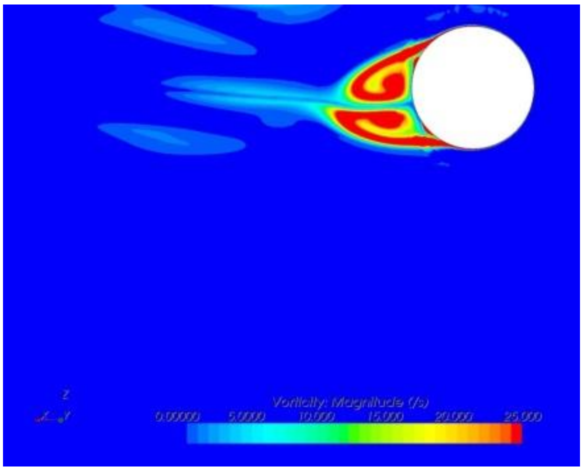

Fig 5. Vortex shedding at time, t =1.092 sec.

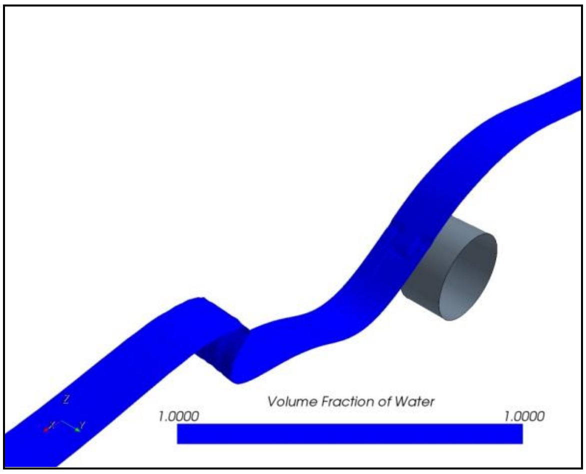

Fig 6. Free surface development at time=2.541 sec

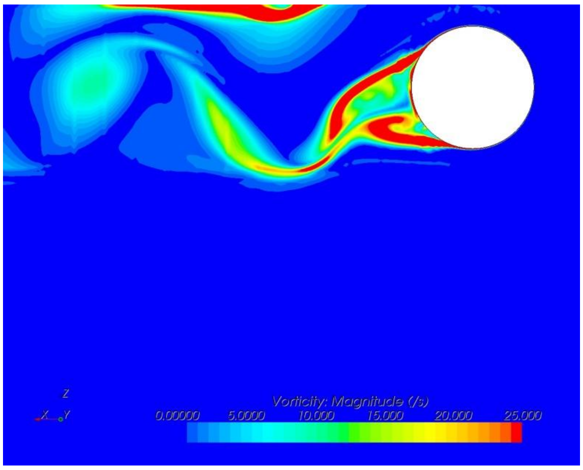

Fig 7. Vortex shedding at time, t = 2.541 sec

ratio 0.5. There is considerable flow over the cylinder and hence considerable vorticity generated, nominally with shedding into the wake. Eventually there is a Von-Karman type vortex shedding for this kind of flow which can be seen in Figure 4 where the free surface has only started to build up and absolutely no vorticity generated from the surface. One of the major interests is to study the influence of the surface vorticity in the main vortex shedding. As the time passes on the free surface starts to breakup and causing a surface vorticity and at 8 sec the surface starts to breakup massively and causing a massive surface vorticity in a haphazard way which soon start to disturb the main vortex shedding and eventually the uniform frequency of Karman type vortex shedding.

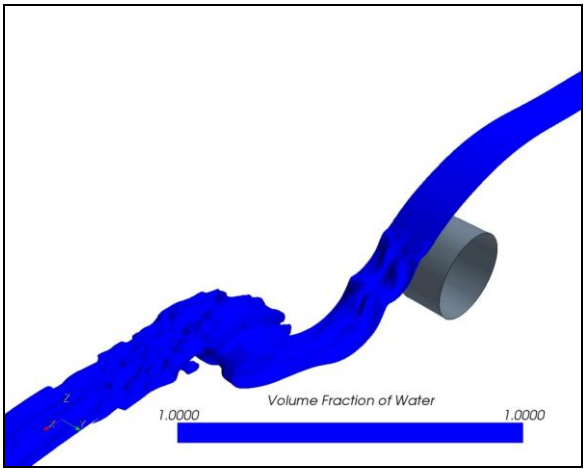

Fig 8. Free surface development at time=3.645 sec

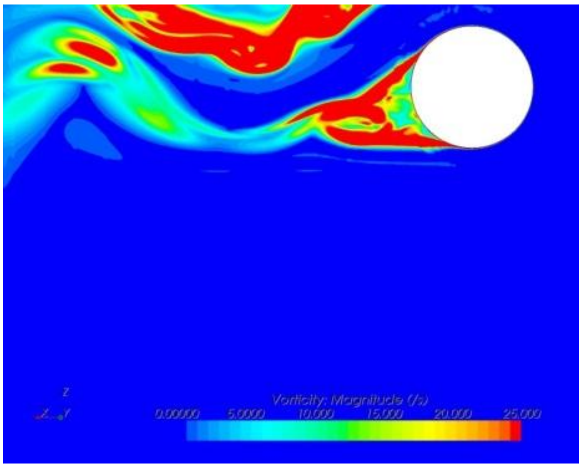

Fig 9. Vortex shedding at time, t = 3.654 sec

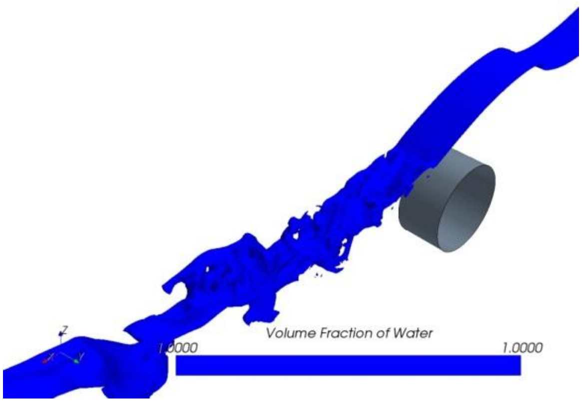

Fig 10. Free surface development at time=8.148 sec

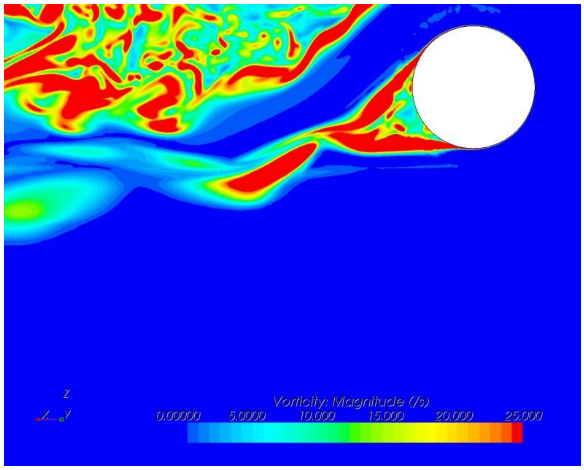

Fig 11. Vortex shedding at time, t = 8.148 sec

3.1 Surface Sharpening And Wave Breaking

In steady flows, surface curvature leads to the kinematic generation of vorticity equal to twice the local angular velocity times the local curvature (*e.g.* Lugt [9], Rood [10]). Thus where the surface is strongly distorted, i.e. highly curved, considerable surface vorticity results. Presumably strong surface curvature and associated large velocity gradients also assist this vorticity to first diffuse and then convert into the main flow to interact with existing wake vorticity. From the first figure till the last we can see the development of free-surface at the same time interval as the vorticity given above .At the time of 1.092 sec there is a smooth free-surface development at the same time we see the vortex field is almost free from the surface vorticity because there is no surface breaking happening and as the time progresses the surface starts to sharpen and at approximately 3.0 sec after flow has developed it starts to break. And after 8 a massive surface breaking happing due to which a massive surface voticity field has been produced which affects main stream vorticity field.

3.2 Velocity Contour

When circulation is zero, the uniform stream approaching from the right divides into two symmetric flows, one going over the cylinder, the other flowing under it. The two flows connect again downstream of the cylinder. The flow field is symmetric with respect to the x axis. Two fluid particles immediately above and below the upstream stagnation point travel the same distance around the cylinder and then meet again at the downstream stagnation point in Figure 12. In Figure 13 and Figure 14, when circulation is increased, the stagnation points move towards the lower half of the cylinder so that the two companion fluid particles follow different routes to reach the downstream stagnation point. In particular the fluid particle that travels above the cylinder makes a longer route with respect to its companion, but it travels fast enough to arrive at the same time at the downstream stagnation point.

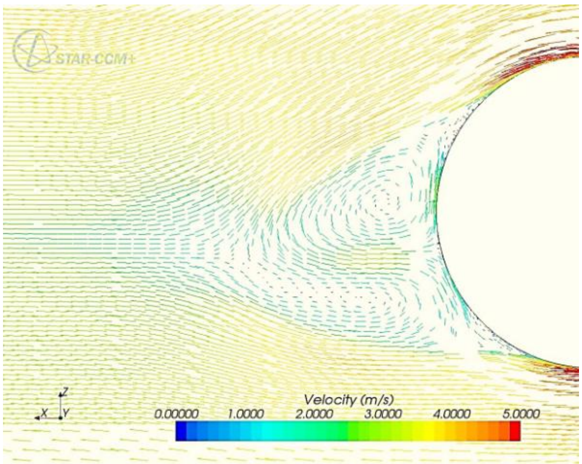

Fig 12. Velocity & direction of fluid particle at time, *t* =1.092sec

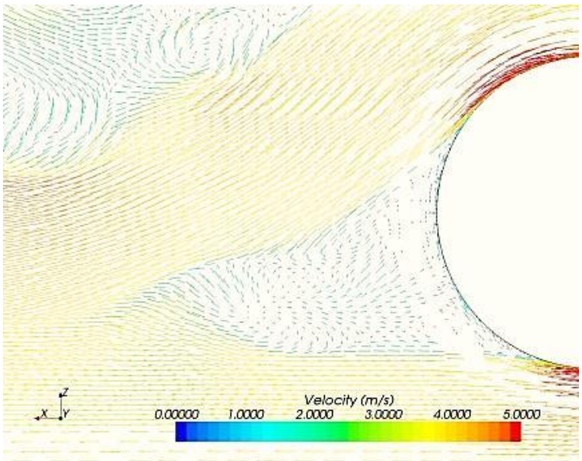

Fig 13. Velocity & direction of fluid particle at time, *t* = 3.645 sec

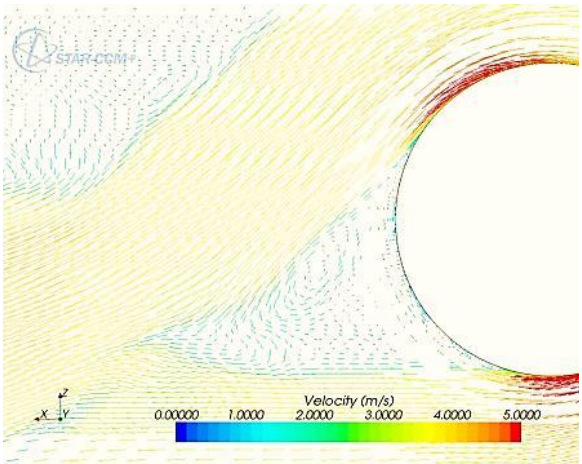

Fig 14. Velocity & direction of fluid particle at time, *t* = 8.148 sec

3.3. Force Coefficient

Figure 15 and Figure 16 shows the time history of force coefficients. From both these figure it is seen that at first for certain times the force coefficients are oscillating and its getting stable gradually as the time passes.

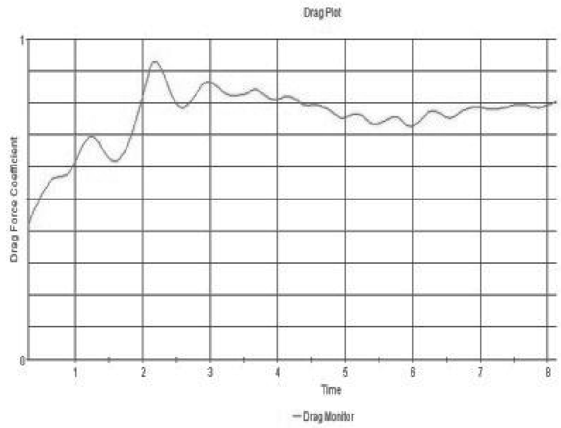

Fig 15. Drag Force Coefficient vs. Time

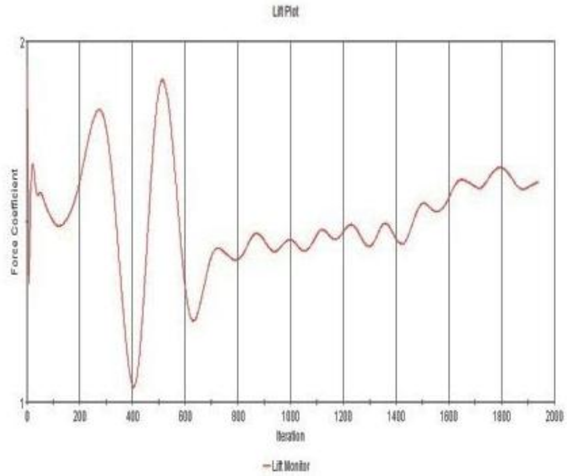

Fig 16. Lift Force Coefficient vs. Time

Table 1 shows the values of force coefficients at different times and Table 2 shows the RMS values of the force coefficients.

Table 1: Drag force coefficient

Time (sec)	Drag force coefficient
1.092	0.657395
1.344	0.676632
2.079	0.887192
2.541	0.787962

Table 2: RMS values of force coefficient

Force Coefficient	Value
Drag	0.751749
Lift	1.511984

4. CONCLUSIONS

In this paper numerical simulation of flow past a circular cylinder at high Reynolds number is presented. The flow situation is very complex due to the presence of free surface. The results are compared with the experiments previously done on flow around a circular cylinder and found a good agreement. The vortex shedding, free surface elevation and breaking of free surface captured which shows a good agreement with other experiments done on it. A Karman type vortex shedding occurs behind the cylinder which later disturbed by the vortex coming from free surface due to the breaking of free surface. These results suggest the applicability of our research in real life problem such as: Flow around a shallowly submerged pipeline, Flow around a submersible vehicle.

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