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Low Froude number frequency response of the wake for flow past a cylinder close to a free surface

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Abstract

The behaviour of the wake Strouhal number for flow past a cylinder close to a free surface at low Froude numbers is investigated numerically. The results obtained are compared with those for flow past a cylinder close to an adjacent no-slip boundary. Favorable agreement is obtained despite the large differences in Reynolds number. As the distance between the wall and the cylinder is reduced the Strouhal number, as measured from the time varying lift, increases to a maximum at a gap ratio of 0.70, before decreasing rapidly with shedding finally ceasing altogether at gap ratios below 0.16. The agreement between the results for a free surface and a no-slip boundary indicates that the mechanism behind the suppression of vortex shedding is common.

Introduction

Flow past a cylinder close to a free surface is of immense importance in the design of offshore structures, marine vessels, pipelines and water based power generation systems. As little work has been done in this area to date, with the exceptions being [8], [11], [12], and [6], comparison with the more widely investigated and related case of flow past a cylinder close to a plane no-slip boundary will be sought. Comparison with the case of a cylinder near a no-slip wall is considered as it is envisaged that this problem may highlight some of the distinct similarities and differences between itself and the case of a cylinder close to a free surface at low Froude numbers. For the interaction of vortices with a free surface, it has been shown by [9] that the free surface at low Froude numbers behaves remarkably like a rigid surface, with little or no surface deformation being observed. This suggests that a comparison between the two cases is warranted.

Miyata *et al.* [8] have examined flow past a cylinder close to a free surface both experimentally and numerically. Their experimental and numerical investigation was conducted at a Reynolds number of 4.96×10^4 and at a Froude number (based on cylinder diameter) of approximately 0.24. They note a step-like change in the flow behavior as the submergence depth (gap ratio) of the cylinder is altered. In particular, sharp changes in the Strouhal number are noted. The large jump seen by [8] occurs in conjunction with a notable weakening in the intensity of the spectra, along with the occurrence of a broader range of frequencies; they suggest that the shedding at the smaller gap ratio is less remarkable, which is assumed to mean weaker. While their visualization at this gap ratio suggests that the flow changes with time, there is no explicit evidence that shedding is observed, although no mention of any suppression of shedding is made either.

Sheridan *et al.* [11], [12] and [6], who examined flow past a cylinder close to a free surface using particle image velocimetry (PIV), PIV and a dye tracer technique respectively, illustrate the flow behavior at larger Froude numbers (based on the cylinder diameter) between 0.47 and 0.72. As the surface is capable of supporting much larger surface curvature at these Froude numbers, their results provide limited insight into the low Froude number cases being examined here, although they do indicate the impact that the Froude number has on the results.

Taneda [13] examined the problem of flow past a cylinder close to a solid surface at a Reynolds number of 170. A towing tank experimental rig was used to eliminate the influence of the wall boundary layer that develops when a similar problem is considered in a wind or water tunnel. In particular, [13] noted that at certain submergence depths (a gap ratio of 0.60), that regular vortex shedding was observed, but at smaller gaps (0.10) only a single layer of vortices was seen to be shed and that the wavelength of these vortices tended to increase with downstream distance, with the wake becoming unstable and breaking down after a few wavelengths.

Others such as [2], [1], [3] and [7] have all examined flow past a cylinder close to a no-slip wall, with all apart from [2] observing changes in the Strouhal number with gap ratio.

The primary focus of the current investigation is to examine whether or not changes in the Strouhal number exist, and if so, to find the manner in which the changes occur, as each of the previous examinations seems to have reported slight differences in behavior.

For the case of a free surface, one would expect the pressure gradients mentioned by the above authors to manifest themselves as surface deformations, which will then be dependent upon Froude number. Hence at low Froude numbers where the surface tends to remain relatively flat, it is suggested that similar results may be observable. However, the lack of wall vorticity and the presence of self induced surface vorticity may alter the results in a significant manner.

Numerical Method and Setup

With reference to figure (1), the governing parameters are defined as follows:
Reynolds number $Re = ud/\nu$, where ν is the kinematic viscosity.
Froude number $Fr = u/\sqrt{dg}$, where g is gravity.
gap ratio (submergence depth) h/d.
Strouhal number $St = u/fd$, where f is the shedding frequency.
The current two-dimensional study was performed with the commercially available code, Fluent 5. In order to model the free surface, which in practice is often an interface between water and air, a variant of the the Volume of Fluid (VOF) method as incorporated within Fluent was employed. The reader is referred to [5] for more details on the VOF method, but it essentially calculates

the flow field for a single fluid (with variable density and diffusivity) and determines the degree of mixing between the phases via the void or volume fraction. The scheme used produces results which are second-order accurate in space for velocity and pressure and first-order accurate for the volume fraction. The temporal scheme used is first order accurate. The system setup simply involved the two phases entering into the domain with a uniform velocity at inlet and leaving though an outlet boundary where a pressure boundary condition is prescribed. The properties of the two phases were set as follows:
Density ratio $\frac{\rho_1}{\rho_2} = 100$ Viscosity ratio $\frac{\nu_1}{\nu_2} = 1$.

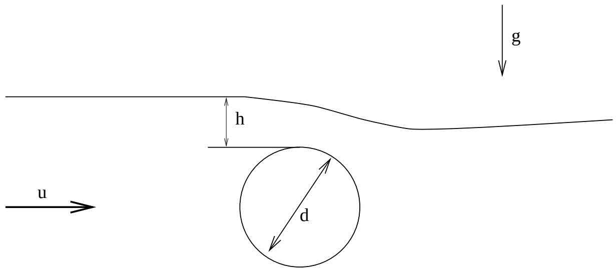

Figure 1: Schematic of the flow arrangement

Results and Discussion

Two Froude numbers were considered in this investigation, namely 0.00 and 0.20. The zero Froude number or free-slip case was considered as it represents the limiting situation in which the free surface is unable to deform. This is achieved numerically by assuming that gravity dominates completely (i.e. $g \to \infty$), and when this is the case, the surface cannot deform and the zero tangential stress condition at the surface implies that it should act like a free-slip wall. All of the numerical simulations were performed at a Reynolds number of 180, the highest value for which flow past a standard cylinder is commonly accepted as being two dimensional

Strouhal number

Simulations were performed for both Froude numbers at the following gap ratios, 0.10, 0.13, 0.16, 0.19, 0.22, 0.25, 0.40, 0.55, 0.70, 0.85, 1.00, 1.50, 2.50, and 5.00. The time variation of the lift force acting upon the cylinder was then analyzed and notable changes in Strouhal number were observed as the gap ratio was altered. The first point to note is that as the cylinder is moved closer to the surface, the Strouhal number increases to a maximum at a gap ratio of 0.70 before decreasing rapidly as the gap is reduced further. The general trend observed compares well with the results of [1], with the normalized Strouhal number and asymptotic distance (distance over which normalized Strouhal number approaches unity) being in good agreement, as shown in figure (2). The labels Angrilli_2860, Angrilli_3820 and Angrilli_7640, in figure (2 refer to the results of [1] at three different Reynolds numbers namely (2860, 3820 and 7640). At smaller gap ratios (which were not considered by [1]), there is a marked drop in Strouhal number and the strength of the time varying lift acting upon the cylinder gets considerably weaker. An investigation of the flow field and the spectra suggests that a weak form of shedding is still observed down to a gap ratio of 0.16, with no shedding noted at smaller gaps. The change in the wake behaviour with gap ratio is shown in figure (5).

Lei *et al.* [7] suggests that the behaviour of the Root Mean Squared (RMS) lift is a better measure for determining when shedding ceases.

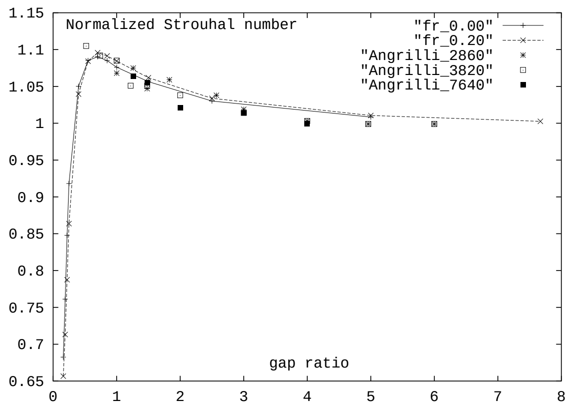

Figure 2: Variation of Strouhal number (normalized with respect to Strouhal number of the reference cylinder i.e. $\frac{St}{St_0}$) with submergence depth, for both the $Fr = 0.00$ and $Fr = 0.20$ cases.

The trends observed here correspond well with those observed by [7] for a cylinder close to a no-slip wall, with both showing similar behaviour over a range of gap ratios. It is only at very small gap ratios that the trends differ, with [7] observing a slight upswing in the RMS lift, which is not seen here at small gap ratios. In addition the gap ratio at which shedding ceases tends to be smaller for the free slip/surface cases. The behaviour of the normalized RMS lift is shown in figure (3). It is suggested by [10] that the difference in the gap ratio at which shedding ceases is due to the ease by which fluid may be entrained upstream, from previous shed vortices. This process is made significantly easier when the adjacent boundary is a free slip/surface one, although the basic mechanism is believed to be the same for both the free surface and no-slip surface cases (however a discussion of the proposed mechanism is beyond the scope of this paper).

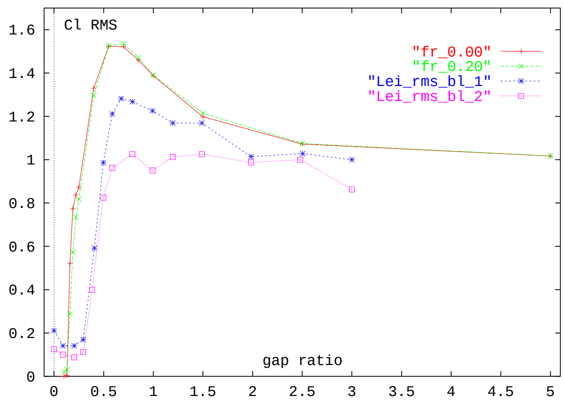

Figure 3: Plot showing the variation of RMS lift coefficient with gap ratio for the free slip (Froude number 0.00) and Froude number 0.20 cases. Also plotted are the results of Lei *et al.* (1999) (for their boundary layers 1 and 2).

Formation Length

The variation of the RMS lift with gap ratio observed in figure (3) is believed to be due to the movement of the formation length (i.e. the position at which discrete vortices roll-up). Due to the inherent asymmetry introduced by the adjacent free surface the formation length could not be measured in the standard fashion (i.e. by calculating the point along a line of symmetry at which the standard deviation in the vertical velocity was a maximum). In the current investigation three different approaches were adopted, and while each yielded a slightly different result, all produced the same trends. The first approach involved calculating the standard deviation of the vertical velocity component at every point in the flow field and then locating the point at which this was a maximum. The second approach was similar, but it involved calculating the point of the maximum standard deviation in the velocity azimuthal to the cylinder. The third method was slightly different as it involved calculating the point (away from the body) at which the standard deviation in the vorticity was a maximum. The first two methods yielded similar positions, while the third produced points closer to the cylinder. Figure (4) shows the variation of the formation length as a function of gap ratio. It is clear that the variation of the RMS lift and the formation location correlate well. The movement of the formation

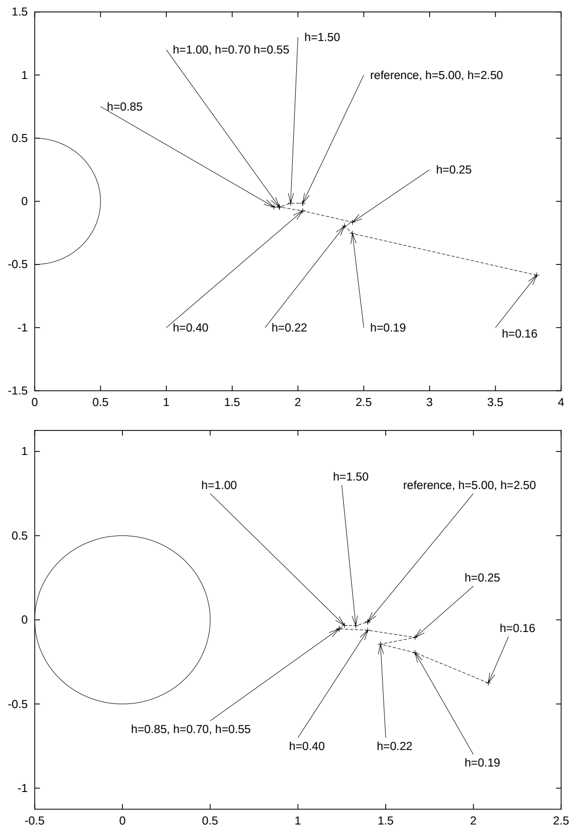

Figure 4: Position of the formation length calculated using the standard deviation in the vertical velocity (top) and vorticity (bottom), for a Froude number of 0.20.

length also explains the observed change in the Strouhal number, with [4] indicating that the period for a fully submerged cylinder at lower Reynolds numbers depends upon the time taken for sufficient vorticity to accumulate outside the region of high shear stress (i.e. in a region from which it can be shed). The lack of change in the Strouhal numbers observed for a cylinder close to a no-slip wall at much higher Reynolds numbers would thus suggest that the movement of the formation length with gap ratio may also be Reynolds number dependent.

Conclusion

Flow past a cylinder close to a free surface at low Froude numbers, is found to display common behaviour with flow past a cylinder close to a no-slip wall, at least in terms of behaviour of the Strouhal number. This suggests that the observed changes (which have been noted by others to occur over a wide range of Reynolds numbers) are primarily governed by the basic geometry, and not by the peculiar characteristics of the adjacent boundary condition.

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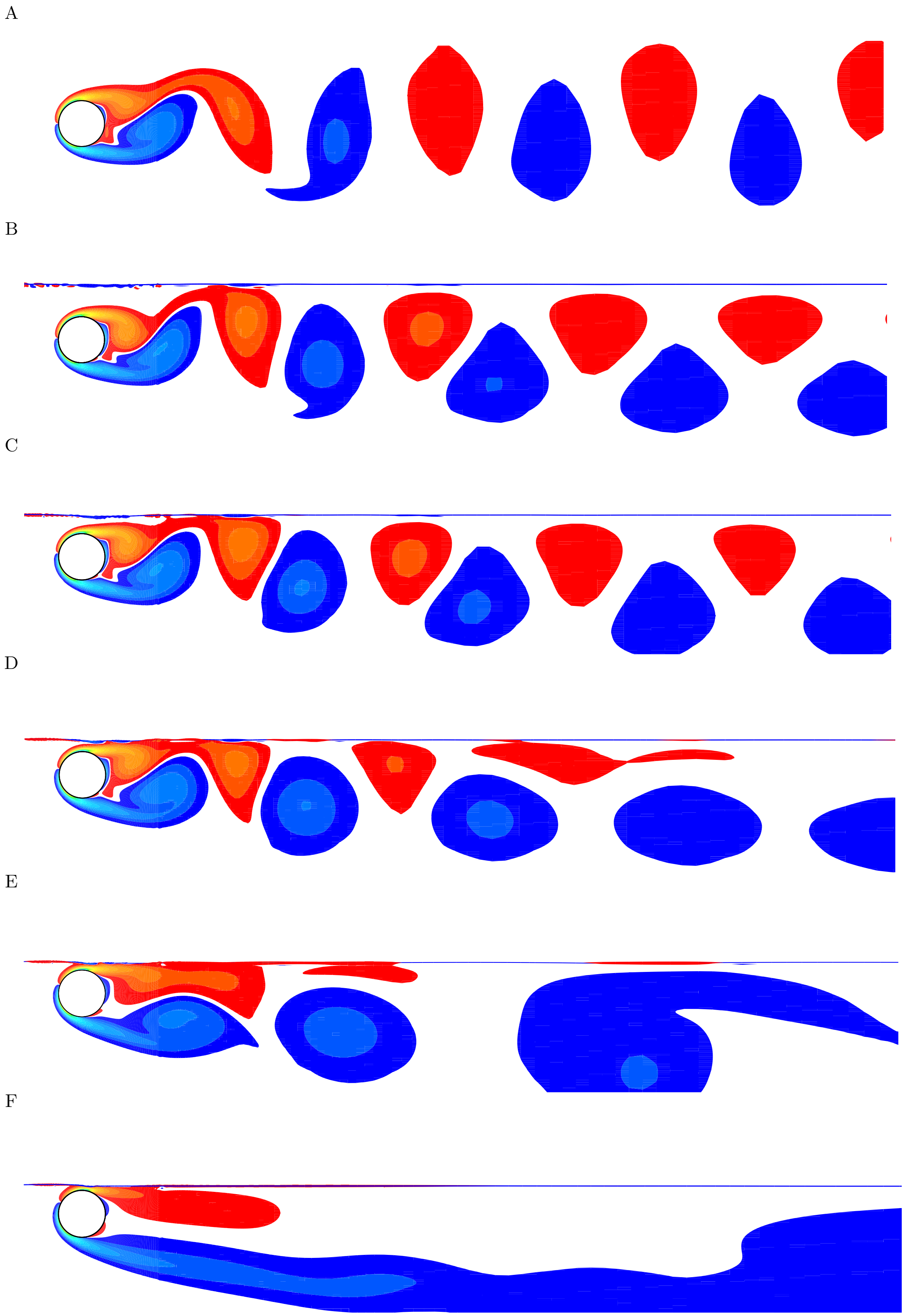

Figure 5: Vortex street plots for: (A) the reference cylinder, (B) gap ratio 0.70 and Froude number 0.20, (C) gap ratio 0.40 and Froude number 0.20, (D) gap ratio 0.25 and Froude number 0.20, (E) gap ratio 0.16 and Froude number 0.20, (F) gap ratio 0.10 and Froude number 0.20