14th Australasian Fluid Mechanics Conference
Adelaide University, Adelaide, Australia
10-14 December 2001

Metastable wake states for flow past a cylinder close to a free surface

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Abstract

For flow at a fixed gap ratio and Froude number, two distinctly different wake states are observed with the flow passing over the cylinder tending to switch from a state of attachment to the free surface, to one of separation from it, and then back again in a pseudo periodic fashion. The two dimensional numerically predicted behaviour is found to compare favourably with the experimental observations of Sheridan *et al.* (1995) and Sheridan *et al.* (1997), despite the large difference in Reynolds number.

Introduction

Flow past a cylinder close to a free surface has relevance to the design of offshore structures and vessels, while also being of particular interest for the detection of submarines via remote sensing satellites. It has been shown by [7], [8] and more recently by [6] that the wake of a cylinder close to a free surface may exhibit more than one state at a fixed point in parameter space. The behaviour of the wake under these circumstances was deemed by [7] to be metastable, as each wake state displayed only a limited degree of stability.

Before entering into a discussion on the metastable wake states which were observed by [7], [8] and [6], it is perhaps profitable to draw attention to what types of flow behaviour have been seen in the region of parameter space that will be considered here. The current study will restrict itself to flow at a Froude number of 0.55 and a gap ratio of 0.40. [8] note that at a Froude number of 0.60 and for gap ratios between 0.75 and 0.24, the flow passing over the cylinder, which in the foregoing will be referred to as a 'jet', tended to progressively move from being attached to the free surface through to being almost attached to the rear of the cylinder. These states are illustrated schematically in figure (1).

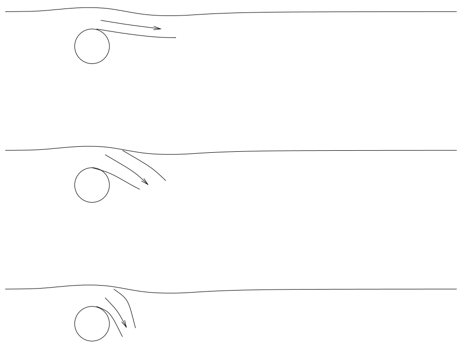

Figure 1: Schematic diagram illustrating the three basic wake states observed by Sheridan *et al.* (1997).

Although the particle image velocimetry (PIV) approach adopted by [7] and [8] yields instantaneous flow fields, they were not in a position to give much detail with regard to the transient nature of the flow states. However, it is reasonable to assume that the flow field is time dependent. [2] also examine this flow but at a Froude number of 0.53, with their dye tracer technique indicating that the flow field was indeed time dependent, with Kármán vortex shedding clearly noted at a gap ratio of 0.75.

For a couple of key cases, both [7] and [8] found that more than one wake state could be observed at a fixed gap ratio and Froude number. For these cases the wake spontaneously underwent transformations between the two states in a pseudo periodic manner. However, [7] were unable to attribute a dimensionless frequency to this behaviour, only indicating that the frequency was roughly two orders of magnitude lower than that of Kármán vortex shedding for a fully submerged cylinder.

The metastable behaviour observed by [7] at a gap ratio of 0.45 and a Froude number of 0.60, involved the 'jet' transiently switching between a state of attachment to the free surface, and a state of separation from it such that it occupied a region of space in between the free surface and the cylinder (i.e. the flow switched between the first and second states in figure (1)). For this case they note that the transition between the two states could be artificially induced by transiently piercing the free surface at a position downstream (presumably at distances greater than 4 diameters) to a depth of approximately 0.4 of a cylinder diameter. They also mention that it was possible to induce hysteretic effects by altering the flow velocity, with this variation typically resulting in a change of wake state.

Sheridan *et al.* [8] also noted that metastable type behaviour occurred at a Froude number of 0.60, and for gap ratios of both 0.31 and 0.59. Their observations at the smaller gap ratio indicated that the 'jet' switched between a state of attachment to the rear of the cylinder, and detachment from it such that it occupied a region of space in between the free surface and the cylinder (the second and third states in figure (1)). At the larger gap ratio, they note that the 'jet' flips between the latter state observed above (i.e. occupying a region in between the free surface and the cylinder) and attachment to the free surface.

Ohring and Lugt [5] have shown for the interaction of a vortex pair with a free surface, that the larger the Froude number the greater the level of surface deformation. This increased curvature combined with the inherently time-dependent shedding of vortices from the cylinder, is thus likely to establish conditions, such that the capacity of the flow around the cylinder to shed, or rather the nature of the absolute instability, will be altered in a time dependent manner. This is not surprising as it is well known that the wake of a fully submerged cylinder is absolutely unstable, and it has been shown by [9] that the wake of a floating cylinder is convectively unstable.

It is suggested by [6] that it is the time dependent skew in the wake, brought about by the deforming free surface, that causes the wake to switch between the two types of instability. Of relevance to this point are the findings of [4] and the speculation by [3], that only a limited degree of asymmetry is required before no time harmonic resonance (or absolute instability) is possible. This suggests that the changes in the wakes behaviour are linked to a change in the nature of the instability associated with the cylinder wake.

Numerical Method and Setup

With reference to figure (2), 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 [1] 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 $\frac{\nu_1}{\nu_2} = 1$.

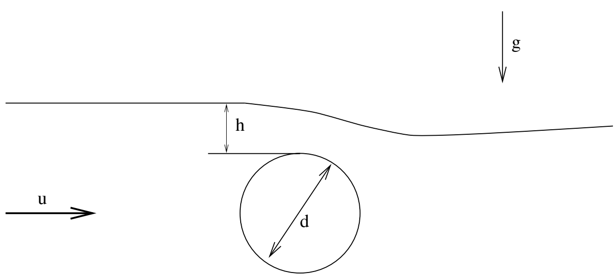

Figure 2: Schematic of the flow arrangement

Results and Discussion

It should be stressed from the outset that the metastable behaviour is time-dependent, and as such it was most clearly illustrated via videos that show the wake development. For the case being considered here (i.e. gap ratio 0.40 and Froude number 0.55) the flow from above the cylinder (i.e. the 'jet') switched between a state of attachment to the free surface and separation from it such that it occupied a region in between the cylinder and the free surface (states one and two in figure (1)).

It is believed that the metastable wake states represent a form of feedback loop, in which the shedding of discrete vortices and their interaction with the free surface induce significant surface curvature, with this curvature then skewing the wake. These changes then alter the conditions which give rise to shedding in the first place, and the absolute instability is weakened or perhaps in some cases extinguished. The weakening of the absolute instability (via the skewing of the wake) hinders the formation of discrete vortices and in doing so it removes the source of the surface distortion, hence allowing the absolute instability to reassert itself. This behaviour is pseudo cyclical and it is dependent upon the response of the free surface to the underlying vorticity distribution, which is highly time dependent. It is believed that it is the structures that form downstream of the cylinder that help govern the degree of skew in the wake, and it is for this reason that it is not surprising that [7] found that external disturbances in the region downstream caused a switching between states. Indeed, their comment that the transformation between the two states could be artificially induced by transiently piercing the free surface at a region downstream (presumably at distances greater than approximately 4 diameters), strongly ties in with what was observed here.

For the case in which the 'jet' is attached to the free surface it is expected that the piercing is likely to induce the roll-up of the negative shear layer and hence result in discrete vortex formation. This will lead to wave breaking and eventually to the separation of the 'jet' from the free surface. On the other hand, when the 'jet' is in the separated state, the transient piecing is likely to restrict the reverse flow in the region behind the cylinder, and in doing so allow the 'jet' to re-attach to the free surface. The hysteretic effect also noted by [7] is similarly expected, as velocity changes will influence the Froude number and as such it will alter the surface curvature and the vorticity dynamics of the wake.

The changes in the behaviour of the wake should make themselves apparent in the lift force acting upon the cylinder. Such time dependent changes can then be measured in terms of a non-dimensionalized shedding frequency or Strouhal number. Figure (3) shows the behaviour of the lift trace and its Fourier transform, while figure (4) shows a close up view of the lift signal with the labels denoting the frames shown in figure (5).

The metastable behaviour has a clear impact upon the lift with the separation of the 'jet' from the free surface resulting in a decrease in the lift force acting upon the cylinder. This behaviour is shown in both figures (4) and (5). Figure (5) shows both the particle transport (with the particles coloured by release height) and the vorticity fields at a few key instants in the metastable cycle.

It should be emphasized that the 'jet' tends to spend most of its time separated from the surface, with the movie for this case showing only limited periods of attachment. The other interesting point is that even when the 'jet' is detached, a limited form of shedding still persists, however, the negative vortices decay very rapidly with downstream distance, such that they are no longer observed after a mere 5 diameters.

As indicated by [6] when the 'jet' separates from the free surface the particle transport movies highlight the

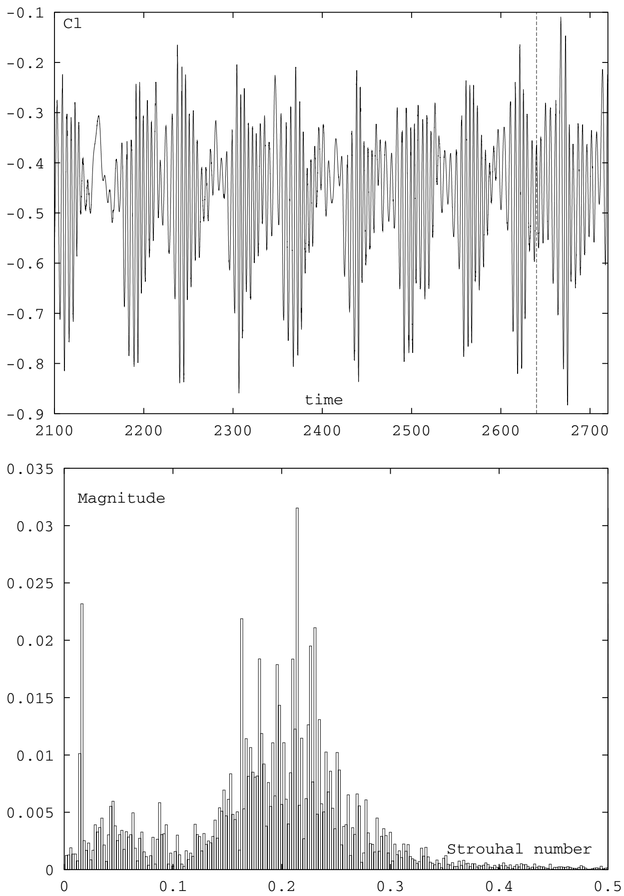

Figure 3: Plot showing the lift trace and its spectra for a gap ratio of 0.40 and a Froude number of 0.55. The region to the right of the dashed vertical line is shown in figure (4).

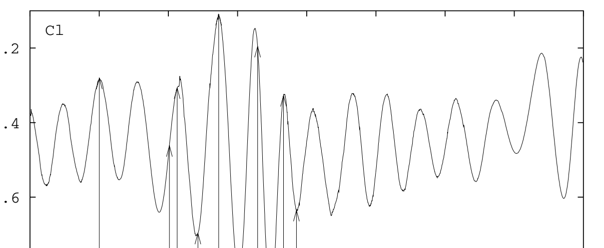

Figure 4: Close up view of the lift trace for a gap ratio of 0.40 and a Froude number of 0.55 The letters (A to J) denote the frames shown in figure (5).

more recirculatory nature of the wake, with much of the fluid passing over the cylinder being transported downstream via entrainment into larger scale positive vortical structures. The recirculatory behaviour results in a significant slowing and at some points in a reversal of the flow close to the free surface at positions downstream of the cylinder. The fluid within this zone has a particularly long residence time, with its dominant mode of removal being via entrainment into the larger scale vortical structures, which tend to form at locations further downstream. These larger scale structures typically from the coalescence of two or more positive vortices from beneath the cylinder.

The formation of a large recirculation bubble is largely consistent with notion that the wake is becoming convectively unstable. Hence as suggested by [6] it appears as if the metastable wake states represent a loose border in parameter space between an absolute and a convective instability. Such that the level of surface deformation and hence skew at any particular instant, determines the wake behaviour.

Conclusion

It is suggested here as in [6] that the metastable wake states represent a loose form of boundary between and absolute and a convective instability. This assertion is supported by the findings of [4] and [3] which suggest that only a limited degree of asymmetry is required before an absolute instability is lost. For this case the switching between the two types of instability occurs as a result of the altered surface curvature, which introduces sufficient skew to transiently alter the nature of the instability.

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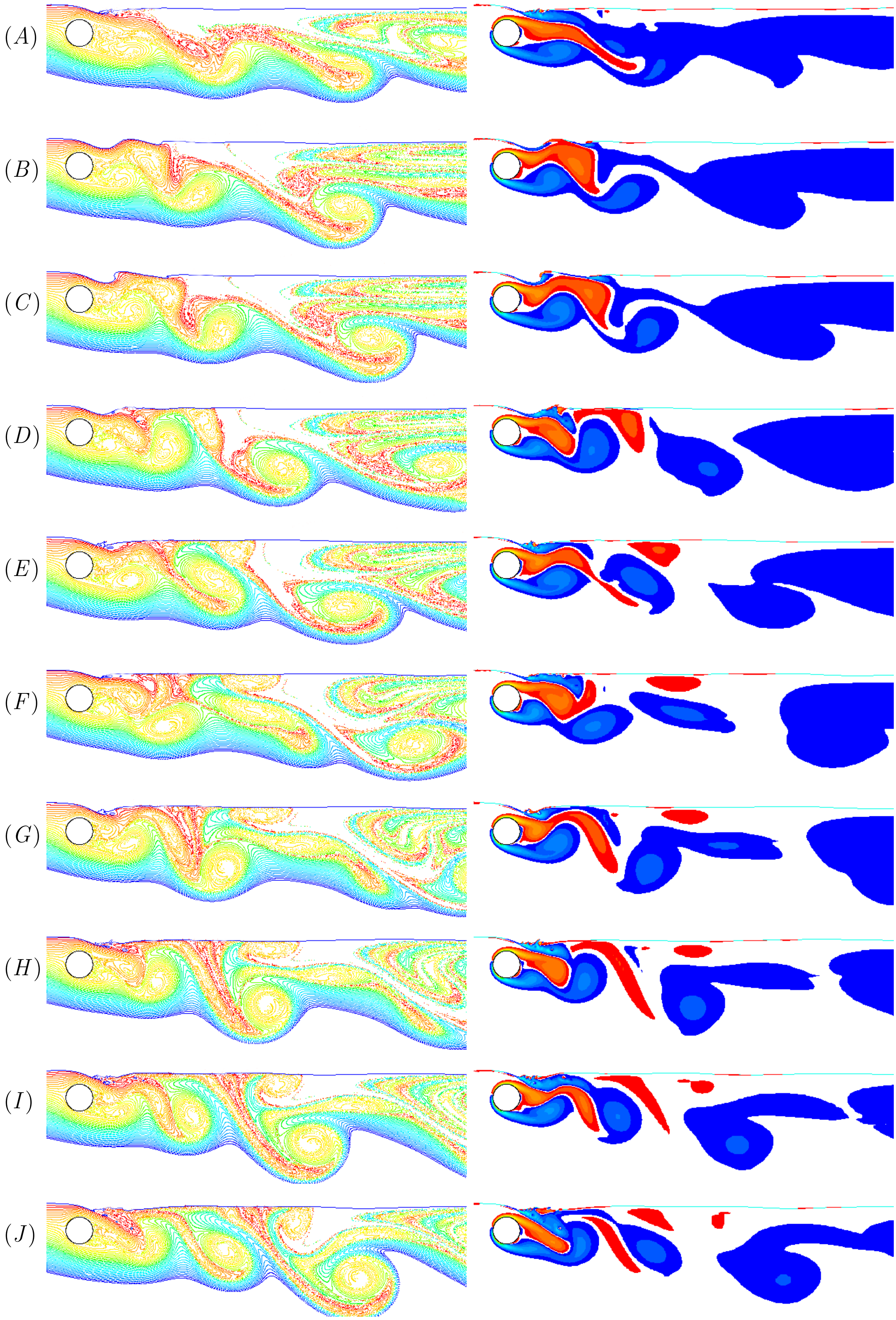

Figure 5: Particle transport and vorticity plots showing the points A to J denoted in figure (4) (gap ratio 0.40, Froude number 0.55).