STUDY OF A TETHERED CYLINDER IN A FREE STREAM

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Abstract: This investigation considers the case of a buoyant rigid tethered cylinder. The response of the cylinder, in particular its layover angle and flow-induced motion, is considered for a range of flow velocities and mass ratios. At lower mass ratios ($0.54 < m^* < 0.72$) two distinct states are observed, where the intermittent switching transition between the two states is characterised by a jump to large amplitude oscillations, and a corresponding jump in both the mean tether angle and the drag coefficient. There is a good collapse of data, in particular the collapse of the mean layover angle, when plotted as a function of the buoyancy Froude number, defined as $Fr_{buoyancy} = U / ((1-m^*)gD)^{0.5}$.

Key words: **Tethered, Cylinder, experimental, displacement, vortex-induced, vibration**

1. INTRODUCTION

The instabilities generated by a fluid flow around a body can result in large scale vibrations of the body. A number of previous investigations have considered the case of a cylinder constrained to move transverse to a free-stream flow, eg Govardhan and Williamson (2000). Several studies have considered motion in the inline and transverse direction for both forced and free oscillation, see, for example, Jauvtis and Williamson (2003) & Jeon and Gharib (2001). A closely related problem is that of tethered bodies, where the body is constrained to move about a tether point. Despite the relevance of these cases to tethered cylinders submerged in a current they have received little attention until the recent numerical work on a tethered cylinder by Ryan et al. (2004) & Pregnalato et al. (2002).

In this experimental investigation the response of a tethered cylinder normal to a free-stream flow is investigated over a range of flow speeds and mass ratios. The experimental layout and a number of important parameters can be seen in Figure 1.

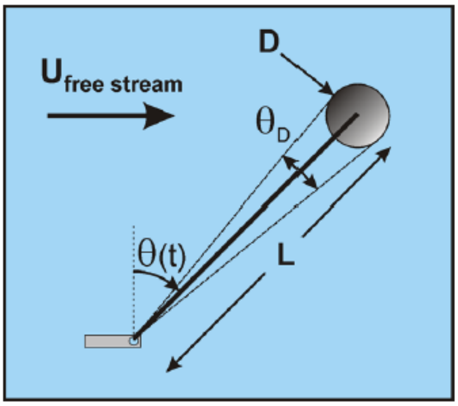


Figure 1 Schematic of the experimental setup.

The constrained radial motion of the tethered cylinder system means that relative to the free stream the cylinder motion is a mix of both inline and transverse movement. For very long or infinite tether lengths, the motion of a tethered cylinder can approach that of the in-line or transverse case. One of the interesting features of the tethered cylinder system is that the geometry of the cylinder motion relative to the free stream changes with the mean tether angle. At low flow velocities the motion is predominantly inline with the flow, whereas at high velocities a larger drag force dictates that the cylinder motion is mostly transverse to the free stream.

An elastically mounted cylinder has been shown by Govardhan and Williamson (2000) to exhibit 2 or 3 response branches as the flow rate of the free stream is increased, where the number of response branches depends on the mass-damping of the system. Govardhan and Williamson (2002) investigated the response of a lightly damped cylinder mounted with no restoring force (k = 0). The response of the system was shown to be largely dependent on the mass ratio m*. Without the restoring force large oscillations were found only to occur below a critical mass ratio, m^*_{crit}. For mass ratios above m^*_{crit} only very small scale oscillations were observed.

The study of Ongoren and Rockwell (1988) found that a cylinder undergoing forced oscillations at a range of inclination angles exhibits a number of different shedding modes. Transverse oscillations (90° to the flow) resulted in stable anti-symmetric wakes. As the inclination angle was decreased, so the cylinder oscillated in the inline direction (0°), symmetric near wake structures were observed. Interestingly, the wake exhibited continual intermittent switching between symmetric and anti-symmetric modes, with the anti-symmetric modes becoming less dominant as the inclination angle decreased. The high level of mode competition indicates that the forced inclined oscillations did not produce a single stable wake state.

The majority of work done to date on buoyant tethered bodies has been on spheres and buoys, typically involving a free surface. The research of Govardhan and Williamson (1997 a & b) found that a fully submerged sphere exhibits large scale oscillations over a wide range of reduced velocities. Interestingly at higher reduced velocities the response of the sphere is not locked-on to its natural structural frequency and its oscillating frequency is significantly less than the corresponding Strouhal frequency of a stationary cylinder.

Until the two dimensional numerical work of Ryan et al. (2002, 2004 a & b) the case of a tethered cylinder has received little attention. At a mass ratio of m* = 0.833 and a constant Reynolds number of 200 the mean tether angle was observed to increase smoothly with increasing reduced free-stream velocity. The continuing increase in tether angle was attributed to the increase in drag force. At low reduced velocities, with an essentially vertical tether, small scale oscillations were observed in the predominantly inline direction. It wasn't until the higher reduced velocities, where motion of the cylinder was mostly transverse that large scale oscillations were observed. Ryan et al. (2002, 2004 a & b) also found that at high amplitude oscillations the mean lift force becomes negative, this will both over estimate the tension in the tether and the structural frequency of the system at high amplitudes.

From the equations of motion the natural frequency of the tethered-cylinder system in analogous to that of a pendulum, where f_N is related to the tension in the tether, T, as seen below in Equation 1.

$$f_N = \frac{1}{2\pi}\sqrt{\frac{T}{m_{cyl+apparent}}} \tag{1}$$

By assuming a net zero lift force both the drag force and tether tension force can be calculated from θ_{mean} and the cylinder buoyancy force. The natural structural frequency of the system, f_N is analogous to that of a pendulum where f_N is related to the tension in the tether T.

$$f_N = \frac{1}{2\pi}\sqrt{\frac{(1-m^*).g}{(m^*+m_a).L^*.D.\cos(\theta_{mean})}} \tag{2}$$

Where L* is the non-dimensionalised tether length L / D, and m_a is the idealised added mass coefficient and D is the cylinder diameter. Therefore the reduced velocity ($U^* = U/f_N D$) is related to the mean layover angle θ_{mean}.

2. EXPERIMENTAL METHOD

A rigid carbon fibre cylinder 16.2 mm in diameter and 594 mm in length is attached to high precision bearings by two 75.0 mm carbon fibre rods at the ends of the cylinder; this gave the model a tether length ratio of L* = 4.63. Ten mass ratios were used for this investigation (m* = 0.54, 0.59, 0.63 0.68, 0.72, 0.76, 0.80, 0.87, 0.92 and 0.97), all resulting in a positive buoyancy restoring force. The flow velocity was increased from zero to 0.46 ms^{-1}, giving a maximum Reynolds number of 13,700.

The motion of the tether is in one plane and constrained to move in the arc subtended by the tether length. A 25 Hz PAL video camera was used to track the cylinder and the system is calibrated to reduce optical distortion. For each free stream velocity 16,384 data points were collected and the mean tether angle θ_{mean} and the normalized oscillation amplitude (1/2 the peak to peak value) θ^*_{std}, were calculated.

3. RESULTS AND DISCUSSION

Figures 2 - 4 suggest the existence of two different wake states, largely dependent on m*. The jump in states is characterised by a jump in the amplitude of oscillation θ_{max}, mean layover angle θ_{mean}, and drag coefficient C_D.

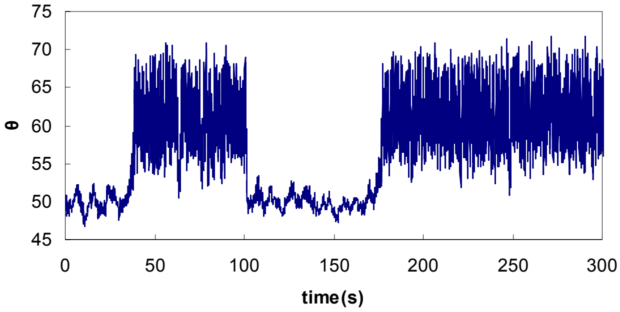
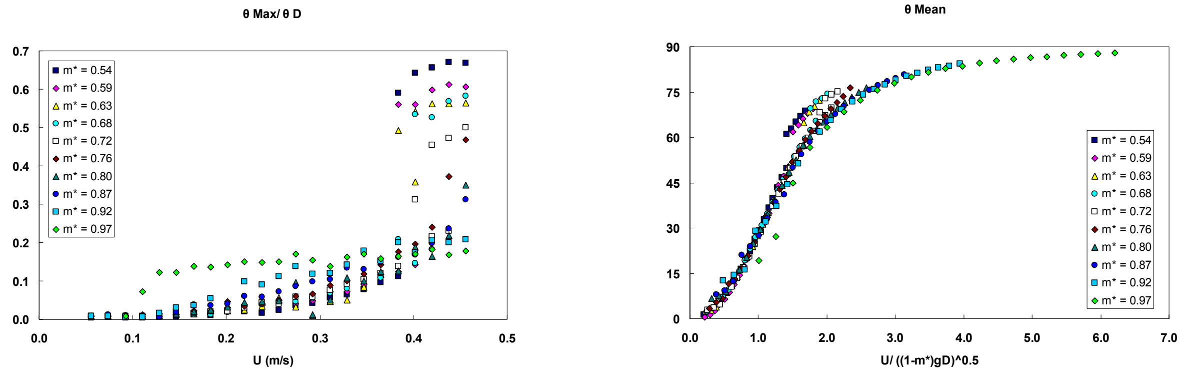


Figure 2. Time trace of angular displacement showing the intermittent switching of response modes (m*=0.54, U=0.38m/s).

1. For low mass ratios m* < 0.72 there is a jump in the amplitude of oscillation. θ_{max} increases gradually with increasing flow speed from rest until an abrupt jump in $\theta_{max.}$
2. For higher mass ratios m* (0.76 $\leq$ m* $\leq$ 0.97) no jump is observed. θ_{max} increases gradually with U and the drag coefficient remains constant at about 0.9.



a) θ_{max} / θ_D vs. U for m* = 0.54 – 0.97 **b) Collapse of θ_{max} data to the Froude buoyancy**

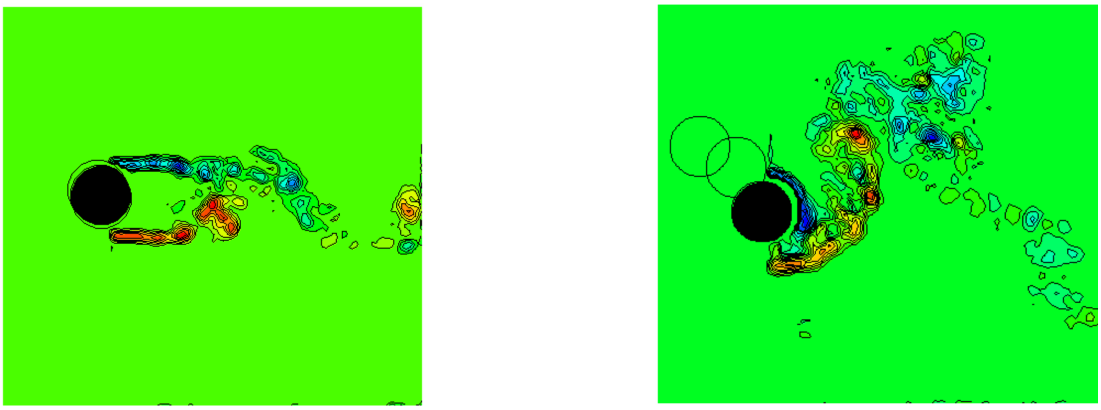
Figure 3 Effect of flow rate on the angular displacement of the tethered cylinder for a range of mass ratios.

The data in Figures 3 (a) and (b) would have the same general form had it been presented using either the traditional Froude or Reynolds numbers, as *g D* and *v* are constant. Despite the fact that these non-dimensional numbers incorporate some important aspects of the tethered cylinder system the data does not collapse to any of the response parameters. Defining a new Froude number using the buoyancy force instead of the gravity component gives a much better collapse of data.

$$Fr_{bouyancy} = \sqrt{\frac{fluid \cdot inertial \cdot force}{bouyancy \cdot force}} = \frac{U}{\sqrt{(1-m^*)gD}} \qquad (3)$$

As seen in Figure 3(b) the data collapses well to this new Froude Number. The lower line represents the cylinder before the jump, whereas the upper line represents the state after the jump.

Figure 4 shows two typical instantaneous PIV images of a cylinder with mass ratio of m* = 0.54 before and after the jump. Figure 4(a) is at a flow speed of 0.292ms^{-1} and a narrow wake is observed, with symmetric von Kármán shedding. Figure 4 (b) is after the jump with the cylinder at the bottom of its travel, at a flow speed of 0.456ms^{-1};here the wake has become more disorganized.



(a) (b)

Figure 4. PIV images showing different wake states (a) before (b) after the jump.

4. CONCLUSION

This paper describes the motion of a tethered rigid cylinder in a uniform free-stream. The cases of elastically and rigidly mounted cylinders are well documented; however, tethered bodies have received relatively little attention. The motion of the cylinder is constrained to move on the arc subtended by the tether length. Both the motion of the cylinder relative to the free stream and the natural frequency of the system change as the layover angle is increased.

Despite the complexity of the tethered cylinder system the mean layover angle data collapsed excellently to the Froude number, where the Froude number used in this investigation represents the ratio of the inertia force to the buoyancy force.

Two distinct mode states were observed. Significant amplitude oscillations were observed for mass ratios below 0.72 indicating the existence of a critical mass ratio. While the motion was typically periodic in nature, the cylinder's oscillations were less sinusoidal than for an elastically mounted cylinder at similar Reynolds numbers.

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