NEW METHODS FOR SUPPRESSING VORTEX-INDUCED VIBRATION OF CIRCULAR CYLINDERS

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ABSTRACT

The paper describes the results of an investigation to find a vortex-induced vibration suppression device that operates effectively and also reduces drag below that of an equivalent plain fixed circular cylinder. Measurements are presented for a cylinder with low mass and damping which is free to respond in the cross-flow direction. It is shown how vortex-induced vibration can be practically eliminated by using free-to-rotate, two-dimensional control plates. Unlike helical strakes, the devices achieve VIV suppression with drag reduction. The device producing the largest drag reduction was found to have a drag coefficient equal to about 70% of that for a plain cylinder at the same Reynolds number.

1. INTRODUCTION

Vortex-induced vibrations (VIV) are a continuing problem in many branches of engineering and can be particularly severe for the risers used in deepwater offshore oil operations. A widely used method for suppressing VIV of long slender bodies of circular cross section is the attachment of helical strakes. Developed originally in the wind engineering field, strakes suffer from two major problems: the first being that they increase drag and the second that, for a given strake height, their effectiveness reduces with decreases in the response parameter $m^*\zeta$, where m^* is the ratio of structural mass to the mass of displaced fluid and ζ is the structural damping expressed as a fraction of critical damping. Whereas a strake height of 10% of cylinder diameter is usually sufficient to suppress VIV in air at least double this amount is often required in water, and this increase in height is accompanied by a corresponding further increase in drag. For a fixed cylinder it is known that if regular vortex shedding is eliminated, say by the use of a long splitter plate, then drag is reduced hence in theory an effective VIV suppression device should be able to reduce drag rather than increase it. This idea underlies the work presented in this paper.

A simple analysis for a linear oscillator model of VIV (see for example Bearman (1984)), assuming harmonic forcing and harmonic response, shows that response is inversely proportional to the product of m^* and ζ. Hence the most rigorous way to test the effectiveness of a VIV suppression device is to work at low mass and damping. In the experiments to be described in this paper the parameter $m^* \zeta$ was equal to 0.014. Owen et al (2001) describe a method for low drag VIV suppression that had shown itself to be effective down to values of $m^*\zeta$ of about 0.5. This is the attachment of large scale bumps to induce three-dimensional separation and eliminate vortex shedding. However, later experiments at lower values of $m^*\zeta$ have shown a return of VIV with amplitudes similar to those of a plain cylinder. This behaviour has been observed by the authors with even grosser forms of continuous surface, three dimensionality where regular vortex shedding has been eliminated from the body when it is fixed but it returns when the cylinder is free to respond under conditions of low mass and damping. From this experience it is concluded that sharp-edged separation from strakes, with its accompanying high drag, is required to maintain three-dimensional separation and suppress VIV. Hence at values of $m^*\zeta$ typical for risers (<0.1) it seems that three-dimensional solutions are unlikely to provide the required combination of VIV suppression and low drag.

There are a number of two-dimensional control devices to weaken vortex shedding and reduce drag, with the most well known being the splitter plate. In this paper we describe the results of experiments to suppress VIV and reduce drag using various configurations of two-dimensional control plates.

2. EXPERIMENTAL ARRANGEMENT

Experiments have been carried out on various devices fitted to a rigid length of cylinder free to respond in only the transverse direction. A few measurements are also presented for a cylinder free to respond in only the in-line direction. The investigation was carried out in a recirculating water channel with a test section 0.6m wide, 0.7m deep and 8.4m long. The flow speed, U, is continuously variable and good quality flow can be obtained up to at least 0.6 m/s. The cylinder model was constructed from 50mm diameter Perspex tube, giving a maximum Reynolds number of approximately 30,000, based on cylinder diameter D. Models were mounted on a very low damping, air bearing support system spanning the top of the channel. A load cell was attached between the cylinder and the support system to deduce the instantaneous and time-averaged hydrodynamic forces on the cylinder model. In order to obtain the hydrodynamic transverse force acting, the inertia force (cylinder structural mass x acceleration) was subtracted from the force recorded by the load cell. Drag was measured by repeating experiments with the load cell orientated in the flow direction. With the load cell in place, the mass ratio, where mass ratio is defined as vibrating mass divided by the displaced mass of water, was 2. The structural damping was around 0.007, as a fraction of critical damping, giving a value of the product of mass ratio and damping of only 0.014.

Measurements were made using one set of springs and the reduced velocity range covered was from 1.5 to 23, where reduced velocity, V_r, ($V_r = U/Df_0$) is defined using the cylinder natural frequency measured in air, f_0. This frequency is very close to the true natural frequency that would be recorded in a vacuum. It should be noted that a number of researchers define reduced velocity using the natural frequency measured in still water. This frequency is lower than the true natural frequency due to the effect of the water added mass. The only flow variable changed during the course of the experiments was the flow velocity U, which, as for full-scale risers, alters both the reduced velocity and the Reynolds number. The position of the cylinder was measured using a non-contacting displacement transducer so as not to affect the damping level. Throughout the study, cylinder displacement amplitude, A, was found by measuring the root mean square value of response and multiplying by √2. This is likely to give an underestimation of maximum response but was judged to be perfectly acceptable for assessing the effectiveness of VIV suppression devices. Displacement A is non-dimensionalised by dividing by the plain cylinder diameter D.

In addition to response and force measurements, flow visualisation was carried out using laser-illuminated fluorescent dye. Flow field measurements to obtain instantaneous spatial distributions of velocity and vorticity were obtained using a Dantec PIV system.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Plain cylinder

Initially experiments were conducted on a plain cylinder to validate the apparatus and the experimental method. Figure 1 shows transverse amplitude versus reduced velocity and the form of the results is close to that found by other investigators.

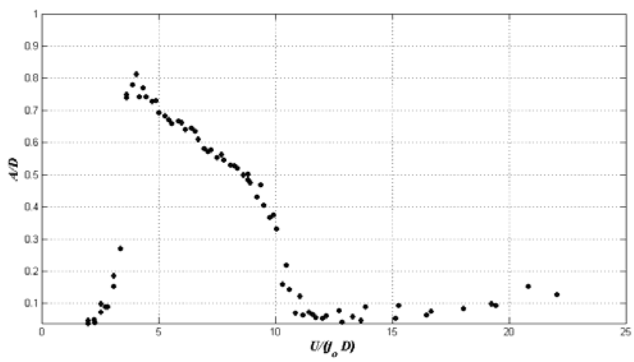


Figure 1: *Response of a plain cylinder versus reduced velocity*

3.2 Fixed splitter plates

Splitter plates could be rigidly attached to the rear of the cylinder and tests were carried out with plates of length 0.5D and 1D. The result in both cases was a very vigorous transverse galloping oscillation that, with increasing reduced velocity, would apparently increase without limit. In the experiment the maximum amplitude of transverse oscillation was limited to 2D and this was reached at a reduced velocity of about 10. Since a device to be used in the ocean must have omni-directional effectiveness the next stage was to pivot the splitter plate about the centre of the cylinder, leaving just a small gap between the plate and the cylinder surface.

3.3 Free-to-rotate splitter plates

Following the disappointing results with a fixed plate, it was hoped that a plate free to rotate might provide sufficient hydrodynamic damping to suppress the galloping. However, when a free-to-rotate (f-t-r) splitter plate was used a totally unexpected result was obtained. There were found to be two stable positions for the splitter plate at roughly ±20º to the free stream direction and the plate rapidly adopted one or other of these positions when it was released. VIV was suppressed, throughout the range of reduced velocity investigated, and drag reduced below that of a plain cylinder. Measurements of transverse response for the 1D f-t-r splitter plate are shown in figure 2 and time mean drag coefficients are plotted in figure 3. Results for a plain cylinder, fixed and free, are shown for comparison. The results for other devices are also shown in these figures and they will be referred to later.

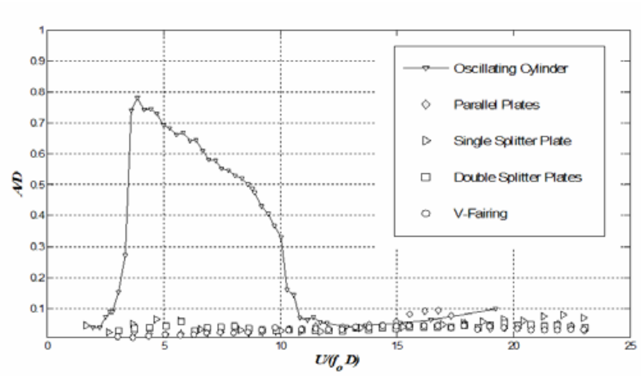


Figure 2: *Amplitude of vibration versus reduced velocity*

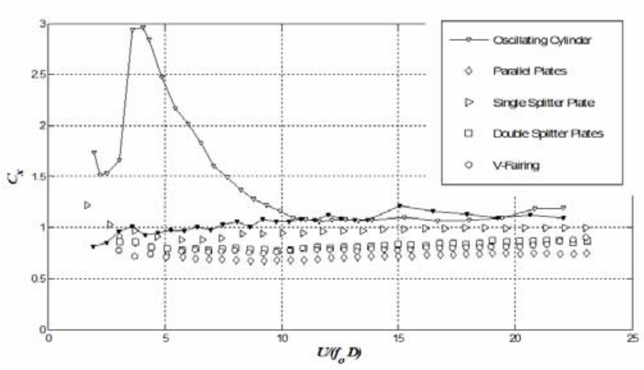


Figure 3: Drag coefficient versus reduced velocity. In addition to the key in the figure; ●, fixed, plain cylinder.

Flow visualisation showed that on the side to which the plate deflected the separating shear layer from the cylinder appeared to attach to the tip of the plate and this had the effect of stabilising the near wake flow. Vortex shedding was visible downstream but this did not feed back to cause vibrations. An unwanted effect was that a steady transverse lift force developed on the cylinder. The splitter plate was free to rotate so the force, caused by differing flow on the two sides of the combination of cylinder and splitter plate, must be acting primarily on the cylinder rather than the plate.
As shown in figure 4, the direction of the force was opposite to that which occurs on an aerofoil with a deflected flap, and caused the cylinder to adopt a steady offset position to the side to which the splitter plate deflected. It was this force which was responsible for the strong galloping response with the fixed splitter plate. As a cylinder with a fixed

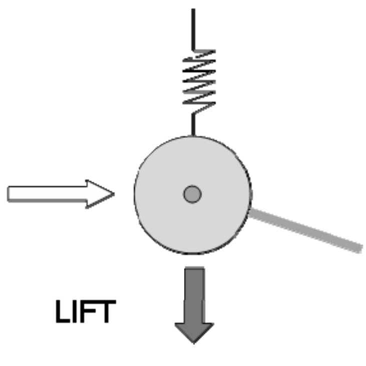


Figure 4: *Diagram showing offset position of plate and direction of steady lift force*

splitter plate aligned with the free stream plunges downwards, say, the instantaneous flow direction is approximately the same as that shown in figure 4. A transverse force develops in the same direction as the cylinder motion, energy is extracted from the free stream and galloping oscillations sustained.

All the results presented so far have been for a f-t-r plate having a length equal to a cylinder diameter. Further tests were carried out with a series of f-t-r splitter plates with various lengths in order to assess the effect of plate length on VIV suppression effectiveness. The results plotted in figure 5 show that f-t-r splitter plates with lengths between 0.5 and 1.5 of a cylinder diameter are all effective in suppressing VIV. Also they all had drag coefficients below the value for a plain fixed circular cylinder. When f-t-r plates outside the range 0.5D to 1.5D were attached to the cylinder a transverse flow-induced vibration returned.

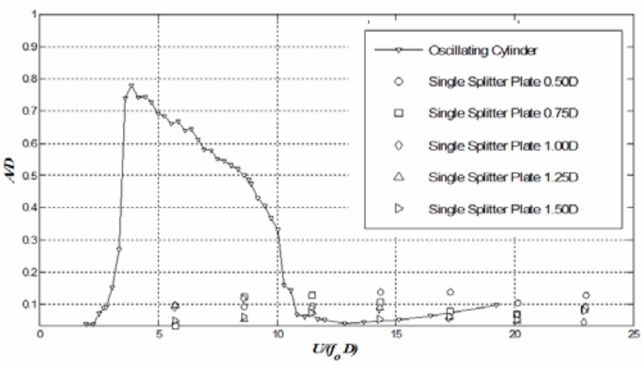


Figure 5: *Effect of free-to-rotate splitter plate length on transverse response*

The plates that successfully suppressed VIV adopted slightly different offset angles, depending on plate length. These steady angles are shown plotted in the lower half of figure 6 and it can be seen that the longer the splitter plate the smaller the angle. The dashed line in the figure is the angle the plate would adopt if it is assumed that the tip of the plate just intercepts a line leaving the shoulder of the cylinder and trailing back in the flow direction. The data generally support the observation that the shear layer from the side of the cylinder to which the splitter plate deflects just reattaches at its tip.

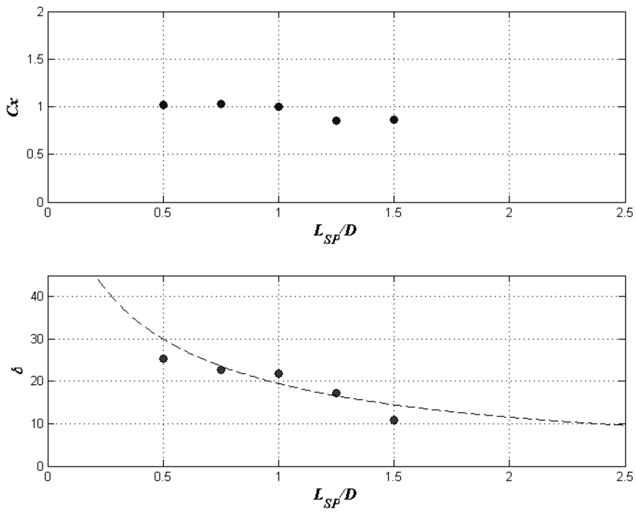


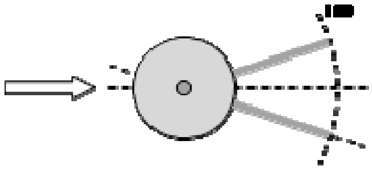
Figure 6: *Drag coefficient and mean deflection angle versus splitter plate length*

Also shown in figure 6 is the variation of drag coefficient with splitter plate length. These results suggest that a successful VIV suppression and drag reduction device using a f-t-r splitter plate can be shorter than one cylinder diameter.

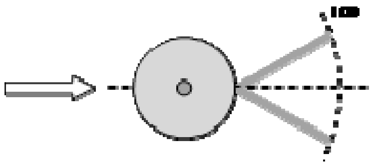
3.4 Pairs of plates

In order to try to eliminate the steady transverse force found for a f-t-r splitter plate, a pair of plates was introduced. The plates were 1D long and set at ±20º to the free stream direction. The angle between the plates was fixed but the pair of plates was free to pivot about the centre of the cylinder. The configuration is shown in the upper part of figure 7. A variation on the double splitter plate design is shown in the lower part of figure 7. This is termed a V-fairing and while the plates meet at the back of the cylinder the combination is still pivoted about the centre. To place the plate tips in roughly the same positions as for the double splitter plate the angle of the plates is increased.

As shown by the results plotted in figures 2 and 3, these configurations suppressed VIV and reduced drag below that of a plain cylinder. They also eliminated the steady side force found with the single plate. With these arrangements the shear layers from the cylinder stabilised and reattached to the tips



Double splitter plate



V-fairing

Figure 7: *Double splitter plate suppressor and V-fairing suppressor*

of the plates. Downstream of the plates vortex shedding was observed but this did not generate an excitation sufficient to cause any serious VIV. Maximum amplitudes recorded were around 5% of the cylinder diameter.

Further variations on the concept of double plates, some inspired by the early work of Grimminger (1945) related to suppressing VIV of submarine periscopes, were also studied. These included plates parallel to the flow and trailing back from the ±90° points on the cylinder. In one case there was a very

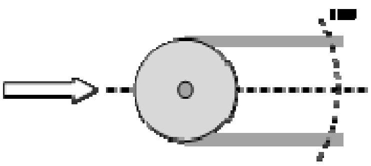


Figure 8: *Parallel plates after Grimminger (1945)*

small gap between the plates and the cylinder (figure 8) and in a second case the gap was set at 10% of the cylinder diameter. The plates trailed back 1D from the back of the cylinder. In Grimminger's experiments the plates were fixed since the flow direction was known but in our work the plates were free to rotate. It was found that the plates with the very small gap give the better performance. As shown in the plots in figures 2 and 3 of amplitude and drag coefficient against reduced velocity, this configuration of plates provided excellent VIV suppression and a reduction in drag below the plain cylinder value.

Table 1 shows values of the drag coefficient for the various configurations tested. The drag coefficients tabulated are averaged over the range of reduced velocity investigated which is similar to averaging over the range of Reynolds number used. A drag reduction from the plain fixed cylinder value of nearly 30% is achieved for the parallel plates with minimum gap. It should be kept in mind that the reductions presented in Table 1 apply to the subcritical Reynolds number range studied in the investigation. There is no guarantee that the same level of reduction will be achieved at much higher Reynolds number when the natural flow separation line moves beyond 90º and the fixed cylinder drag coefficient is lower. In this case the V-fairing or double splitter plates may provide a better solution.

Configuration	Drag Coefficient	% Reduction
Plain fixed cylinder	1.03	0.0
Parallel plates	0.73	29.1
Single splitter plate	0.97	5.8
Double splitter plate	0.82	20.4
V-Fairing	0.79	23.3

Table 1: Drag coefficients and % reduction in drag from a plain, fixed circular cylinder

In the work described so far no mention has been made of sensitivity to two additional parameters: the rotational inertia of the plates and the torsional resistance resulting from friction in the bearings holding the plates. Experiments with mass added to the plates showed no obvious change in behaviour. However, when very low friction bearings were used flow-induced vibration occurred. Very small increases in friction were sufficient to suppress vibration of the plates. We are in the process of quantifying the critical friction level required for effective suppression.

3.4 In-line vibrations

It has been shown here that various arrangements of two-dimensional control plates are effective in suppressing transverse vortex-induced vibrations. However, is this achieved at the expense of larger in-line VIV amplitudes? To answer this question the cylinder support apparatus was rotated through 90° so the cylinder model was free to vibrate in the in-line direction. Experiments were repeated with the various arrangements of plates and the measured in-line amplitudes are shown in figure 9 plotted against reduced velocity. The results for the cylinder without control are also shown and these agree with those found by other investigators.

From figure 9 it can be seen that with the 1D splitter plate fitted, the reduced velocity range for in-line VIV is reduced but the maximum amplitude is little changed from that of the plain cylinder. However, with the double splitter plate and the parallel plates VIV amplitudes are reduced by about 50%. A significant feature of all three devices is that vibration amplitudes at high values of reduced velocity are significantly reduced below those of a plain cylinder. This is likely to be due to the lower drag coefficients of these configurations.

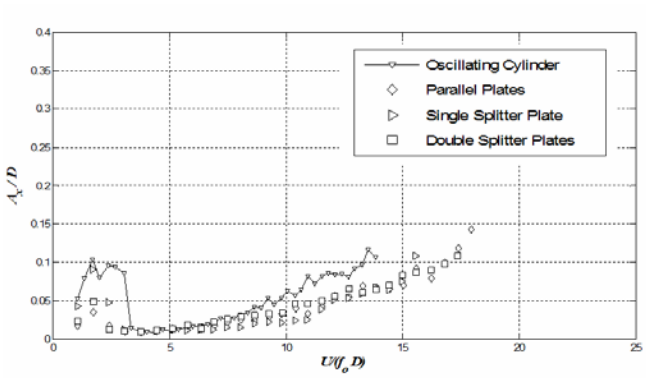


Figure 9: *In-line amplitudes versus reduced velocity*

4. CONCLUSIONS

Suppression of cross-flow, vortex-induced vibration of a circular cylinder, with resulting drag coefficients less than that for a fixed plain cylinder, has been achieved using two-dimensional control plates. This has been accomplished at a value of the combined mass and damping parameter of 0.014. The maximum drag reduction is about 30% and this occurs with parallel plates. A free-to-rotate splitter plate was also found to suppress VIV but this configuration develops a mean transverse force. This force can be eliminated by using a pair of splitter plates arranged so that the shear layers that spring from the cylinder attach to the tips of the plates. In-line vibration amplitudes are equal to or less than those recorded for a plain cylinder. A significant reduction of in-line amplitudes was found when a pair of control plates was used.

5. ACKNOWLEDGEMENTS

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