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VIV AND WIV SUPPRESSION WITH PARALLEL CONTROL PLATES ON A PAIR OF CIRCULAR CYLINDERS IN TANDEM

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ABSTRACT

Experiments have been carried out on two-dimensional devices fitted to a rigid length of circular cylinder to investigate the efficiency of pivoting parallel plates as wake-induced vibration suppressors. Measurements are presented for a circular cylinder with low mass and damping which is free to respond in the cross-flow direction. It is shown how VIV and WIV can be practically eliminated by using free to rotate parallel plates on a pair of tandem cylinders. Unlike helical strakes, the device achieves VIV suppression with 33% drag reduction when compare to a pair of fixed tandem cylinders at the same Reynolds number. These results prove that suppressors based on parallel plates have great potential to suppress VIV and WIV of offshore structures with considerable drag reduction.

Keywords: *VIV and WIV Suppression, Drag reduction, Parallel Plates, Tandem Circular Cylinder.*

INTRODUCTION

The response of an elastically mounted single cylinder under vortex-induced vibration (VIV) is well known and has been reviewed in detail by Williamson and Govardhan [6]. However, when a cylinder is immersed within the wake of another body a more complex phenomenon appears and the response of the elastically mounted body can be very different to the one observed for typical VIV. The wake generated on the upstream body interferes with the downstream cylinder generating fluid forces that can excite the body into higher amplitudes of response. Wake-induced vibration (WIV) occurs whenever two or more cylinders – with sufficiently low mass and damping – are immersed in the interference region of a cylinder wake.

Recently, the main motivation for studying this flow-structure phenomenon is found in the offshore oil industry. A single floating platform is able to accommodate more than 40 risers in complex arrangements together with many other cylindrical structures. As the ocean current changes its direction through the sea depth it becomes practically impossible to avoid flexible structures falling in the wake of each other. As a result, the high probability of pipes developing WIV increases the damage risk of structural fatigue as well as the possibility of clashing between them.

Blevins [4] explains how a cylinder can be excited into wake galloping when it is placed downstream of a fixed cylinder but laterally displaced from the centreline of the wake (staggered arrangement). He shows how the mean velocity profile can input energy into the system as the cylinder oscillates in an elliptical orbit. However, the present work is particularly interested in studying one type of WIV that occurs when a pair of circular cylinders with equal diameters is initially aligned with the direction of the flow (called tandem arrangement). In this arrangement the vortices from the front cylinder impinging on the second cylinder seems to be more significant than the mean velocity profile in the wake. Therefore the quasi-steady approach to classical galloping theory falls short in explaining how wake-induced vibrations are sustained in this case. In this sense, we classify WIV as a type of VIV since the interference

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of the vortices coming from the upstream wake is essential to sustain the excitation mechanism.

Bokaian and Geoola [3] present an interesting study of the response of a downstream cylinder in a tandem arrangement and also relates the dependency of WIV on the structural parameters mass and damping. A better understanding of the physical mechanism behind WIV is emerging from recent works [7, 8, 10, 12]. The main finding being that the excitation of the downstream body is sustained by the unsteady force fluctuations caused by the vortices shed from the upstream body interfering with the downstream one.

We believe that only with a clear phenomenological understanding of the nature of the excitation will it be possible to start the development of suppressors that effectively reduce WIV. To cite an example, Korkischko et al. [9] shows that helical strakes typically effective in reducing VIV on an isolated cylinder are no longer effective if the body is immersed in a wake interference region. In this context, we present an experimental study that is aimed at developing more efficient suppressors for offshore applications.

SUPPRESSION OF VIV WITH CONTROL PLATES

As mentioned earlier, 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.

According to Bearman [2], for example, a simple analysis for a linear oscillator model of VIV 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. As concluded by Assi et al. [13], it seems that three-dimensional solutions like strakes or bumps are unlikely to provide the required combination of VIV suppression and low drag.

In previous works [11, 13] we investigated the efficiency of pivoting control plates as VIV suppressors for a single cylinder. We concluded that suppression of cross-flow and in-line, vortex-induced vibration of a circular cylinder, with resulting drag coefficients less than that for a fixed plain cylinder, is achievable using two-dimensional control plates. This has been accomplished at values of the combined mass and damping parameter up to 0.014, showing that the method has potential applications in the offshore industry. The maximum drag reduction occurred with parallel plates (Figure 3) and is about 38%. A free-to-rotate splitter plate was also found to suppress VIV but this configuration developed a mean transverse force towards the side to which the plate had deflected. This force could 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. Because the parallel plates were found to be the most drag-efficient device to suppress VIV it became the focus of the present investigation.

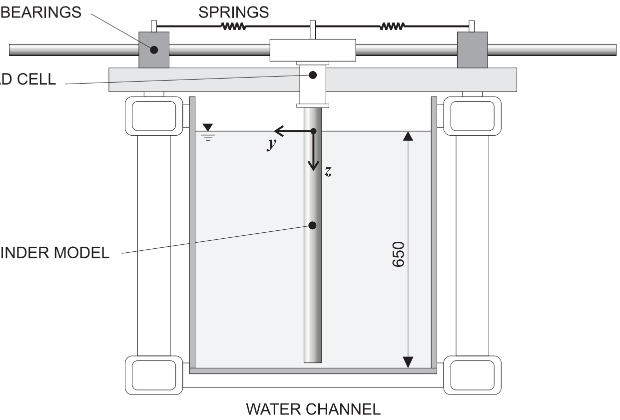

Figure 1. Illustration of the test section. The flow is moving perpendicular to the page plane and the cylinder is allowed to oscillate in the transverse direction (y-axis).

Assi et al. [13] also highlights the importance of torsional resistance in stabilising this type of free-to-rotate suppressors. "It needs to be high enough to hold the devices in a stable position, while still allowing them to realign if the flow direction changes. Devices with torsional friction below a critical value oscillate themselves as the cylinder vibrates, sometimes increasing the amplitude of cylinder oscillation higher than that for a plain cylinder." In the present work we kept the same parameters used by Assi et al. [13] to guarantee that our suppressor is working above the critical value of torsional resistance.

EXPERIMENTAL ARRANGEMENT

Experiments were conducted in the Hydrodynamics Laboratory of the Department of Aeronautics at Imperial College, London. Tests were carried out in a recirculating water channel with a free surface and a test section 0.6m wide, 0.7m

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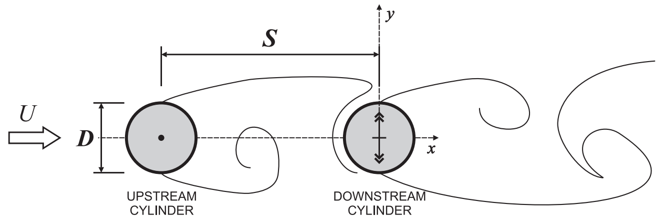

Figure 2. Representation of two circular cylinders aligned in the flow direction (tandem arrangement). Upstream cylinder is fixed and the downstream one is free to oscillate in the transverse direction (y-axis).

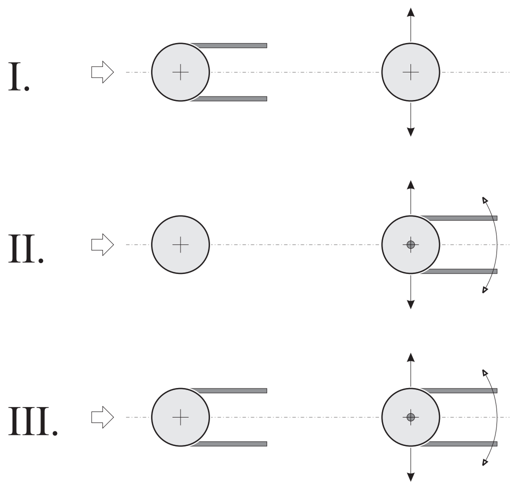

Figure 3. Configurations of downstream and upstream cylinders fitted with f-t-r parallel plates. $S/D = 4.0$.

deep and 8.4m long. The sidewalls and bottom of the section were made of glass, allowing a complete view of the models for flow visualization purposes. The free stream flow speed, U, is continuously variable and flow with turbulence intensity less than 3% can be obtained up to at least 0.6m/s. The circular cylinder models were constructed from 50mm diameter perspex tube, giving a maximum Reynolds number of approximately 30000, based on cylinder diameter D. The models were mounted vertically and passed through the free water surface down to almost the full depth of the section. With a wet-length of 650mm (total length below water level) the resulting aspect ratio of the model was 13. The downstream cylinder was mounted such that there was a 2mm gap between the lower end of the cylinder and the glass floor of the test section.

The upstream cylinder was rigidly attached to the structure of the channel preventing displacements in any direction, while the downstream cylinder was fixed at its upper end to an elastic mounting. Figure 1 shows a schematic representation of the apparatus and helps in describing the operation of the system. The support system is firmly installed on the channel structure and the sliding cylindrical guides are free to move in the transverse direction, defined by the y-axis. A load cell connects the moving parts of the base to the top end of the model and is able to measure instantaneous fluid forces acting on the cylinder in the transverse and streamwise directions.

A pair of springs connecting the moving base to the fixed supports provided the restoration force of the system, setting the natural frequency of oscillation in air (f_0). All the moving parts of the elastic base contribute to the effective mass, resulting in a mass ratio of $m^* = 2.0$, defined as the ratio of the total oscillating mass to the mass of displaced fluid. An optical positioning sensor was installed to measure the y-displacement of the cylinder without introducing extra friction to damp the oscillations. Thus, the cylinder is free to oscillate only in the y-direction with a very low structural damping $\zeta = 0.7\%$ (calculated as the percentage of the critical damping obtained from free decay oscillations performed in air) giving a value of the product of mass ratio and damping of only $m^*\zeta = 0.014$. Measurements were made using one set of springs and the reduced velocity range covered was from 1.5 to 23, where reduced velocity (U/Df_0) is defined using the cylinder natural frequency measured in air. As shown in Figure 2 both cylinders are aligned in the direction of the flow (known as tandem arrangement) with a longitudinal separation, S, measured from the centre of one model to the centre of the other, kept at $S/D = 4.0$.

Throughout the study, cylinder displacement amplitude, A, was found by measuring the root mean square value of response and multiplying by $\sqrt{2}$. This is likely to give an underestimation of maximum response but was judged to be perfectly acceptable for assessing the effectiveness of suppression devices. Displacement A is nondimensionalised by dividing by the plain cylinder diameter D.

FREE-TO-ROTATE PARALLEL PLATES

The suppression device studied was inspired by the early work of Grimminger [1] related to suppressing VIV of submarine periscopes and continues on the investigation of Assi et al. [13]. It is made of two parallel plates running along the whole span of the cylinder. Starting at the $\pm 90°$ points, the plates trailed back $1D$ from the base of the cylinder and were initially aligned to the flow. Both plates were mounted on ball bearings at the extremities of the cylinder and are always parallel to each other, freely rotating as one body around the centre of the cylinder.

The downstream cylinder, which was mounted on the elastic rig, could be fitted with free-to-rotate plates. The upstream cylinder was kept fixed and could be fitted with an identical pair of fixed parallel plates. This way, three different configurations were tested fitting the device on one or both cylinders at a time (Figure 3).

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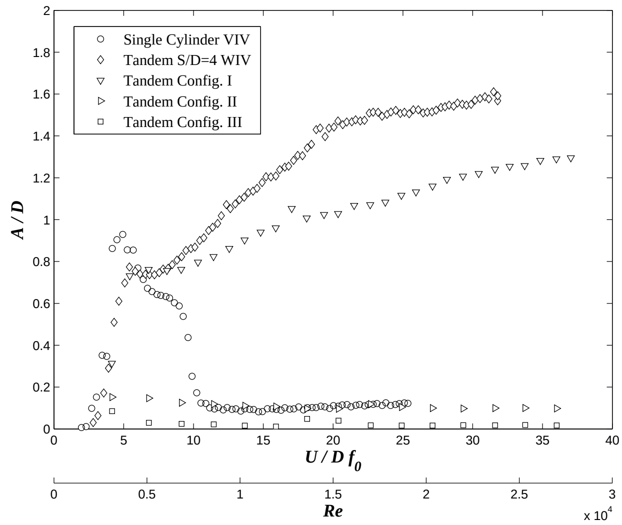

Figure 4. Amplitude of vibration versus reduced velocity. Tandem configurations according to Figure 3.

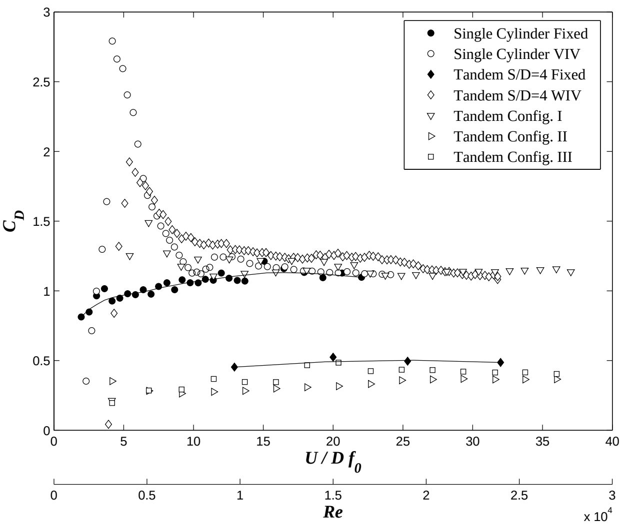

Figure 5. Drag coefficient versus reduced velocity. Tandem configurations according to Figure 3.

RESULTS AND DISCUSSION

Two sets of results are presented in Figures 4 and 5 as reference for comparison. The VIV of a single cylinder is reproduced from Assi et al. [13] and the WIV of the downstream cylinder of a pair is reproduced from Assi et al. [12]. The difference between the typical VIV and WIV excitation is evident in Figure 4: while the single cylinder exhibits the typical pattern of synchronised VIV – with a resonant peak of high amplitude at about reduced velocity 5 and no significant vibration beyond 10 – the WIV mechanism drives the downstream cylinder into high-amplitude vibration increasing with flow speed and persistent for reduced velocities as high as 30.

The results of Assi et al. [13] show that VIV of a single cylinder is completely suppressed by using $1D$ parallel plates. We started our investigation from this point by testing a cylinder fitted with this suppressor but with another identical cylinder positioned $4D$ downstream. First, we observed that the presence of the downstream cylinder does not interfere with the response of the upstream cylinder, but the suppressor is still effective and the cylinder does not present significant amplitude of vibration. This was important to validate our hypothesis that an upstream cylinder fitted with free to rotate (f-t-r) parallel plates would behave as a static cylinder due to the effectiveness of the suppressor, at least for a separation of $S/D = 4.0$ and higher. This being true, we could replace the upstream cylinder by a fixed cylinder fitted with fixed parallel plates and concentrate our attention at the response of the downstream cylinder.

The first set of results shows the response of a plain downstream cylinder when the upstream cylinder is fixed and fitted with fixed parallel plates (Figure 3.I). From Assi et al. [12] we know that the WIV is related to the unsteady vortices from the upstream cylinder and we believe the amplitude of vibration is directly related to the intensity of the vortices formed in the wake coming from the upstream cylinder. From Assi et al. [13] we know that the parallel plates work by delaying the interaction between the two shear layers, thus delaying the formation of vortices and weakening the developed wake formed in the gap between the cylinders. The fact that the drag on a single cylinder fitted with parallel plates is less than the drag on a plain fixed cylinder proves that the wake being generated is weaker. Our results presented in Figure 4 are in accordance with this hypothesis. Since the parallel plates do not annihilate the formation of vortices from the first cylinder, but weakens it, the amplitude of vibration of the downstream cylinder is expected to be less than that observed for a pair of plain cylinders under WIV. This is exactly what we see in Figure 4. Therefore, if only the upstream cylinder is fitted with parallel plates (configuration I) the downstream cylinder would still suffer from WIV, though with a reduced amplitude level.

In configuration II the cylinder fitted with f-t-r plates is positioned downstream of a plain fixed cylinder (Figure 3.II). Now the downstream cylinder presents a level of amplitude around 10% of a diameter, which is the same level of vibration measured for the single cylinder under VIV for higher reduced velocities after the synchronisation region. This level of vibration is already considered to be low and we could say that the parallel plates have successfully suppressed the vibration to desirable values. There is evidence to believe that in configuration II the upstream cylinder is shedding vortices as a single isolated cylinder [12].

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Table 1. Mean drag coefficients and relative drag reduction.

Model	Mean drag	Drag reduction
Fixed single cylinder	1.03	Ref. value
Parallel plates: single [13]	0.63	38%
Fixed tandem S/D=4.0	0.49	Ref. value
Parallel plates: config. II	0.33	33%
Parallel plates: config. III	0.38	22%

Theoretically the wake coming from the upstream cylinder in configuration II has the same characteristics as the wake found between two plain cylinders in tandem arrangement (Figure 2). Therefore the parallel plates must be acting on the shedding mechanism of the downstream cylinder to avoid a vigorous WIV type of response.

From the work of Bokaian and Geoola [3], Zdravkovich and Medeiros [5] and others we know that the mass and damping parameters of the system play an important role and may suppress WIV for certain critical values. We believe that the presence of two long plates along the cylinder axis increase the hydrodynamic added mass and damping in the direction of movement. This change in the effective mass and damping of the system, in comparison to the relatively low value for the plain cylinder, could be responsible for reducing the response but probably not for suppressing the vibration completely. Therefore we believe the plates are acting directly on the two-dimensional shedding mechanism of the downstream cylinder, but the mechanism by which the suppressor is working is not yet clear and further investigation is required. At present, the most straightforward conclusion is that a pair of tandem cylinders with the suppressor fitted on the downstream (configuration II) appears to be suppressing WIV to a satisfactory level.

Figure 5 presents measurements of drag versus reduced velocity. The drag coefficient measured for a single fixed cylinder is plotted as a reference. Noticeably, the drag curve for an oscillating cylinder is much different and shows a maximum of almost $C_D = 3$ at the resonance peak. In the same way, the drag curve for the downstream cylinder of a pair presents a maximum around the VIV resonance and values above those found for a single cylinder for the rest of the reduced velocity range where WIV is present

However, considering a pair of fixed cylinders in tandem arrangement, it is known that the mean flow profile that reaches the second cylinder has a deficit in velocity comparing to the free stream flow. This is due to the slow speed flow developed in the wake of the upstream cylinder. Therefore, the second cylinder of a tandem pair should experience less drag when compared to the first cylinder, which is exposed to the incident free stream U.

Figure 5 also presents drag measurements for the downstream cylinder of a pair that is held fixed. We clearly see that the level of C_D is around half of that found for a single fixed cylinder. Therefore, a correct evaluation of drag reduction for tandem cylinders must take this value as a reference ($\overline{C_D} = 0.49$).

Knowing that the parallel plates are effective suppressing WIV as described above, we can compare its efficiency in reducing drag. Assi et al. [13] showed that the parallel plates installed on a single cylinder can reduce drag by 38% when compared to a fixed cylinder. Now, in Figure 5 we see that the two configurations that successfully suppressed WIV (II and III) also reduced drag when compared to a fixed cylinder in tandem arrangement.

Table 1 summarises the data plotted in Figure 5. The mean drag $\overline{C_D}$ represents the average behaviour of the drag coefficient through the whole range of reduced velocity and Reynolds number studied. We reproduce values from Assi et al. [13] showing that the parallel plates are able to produce a drag reduction of 38% for a single cylinder. Using the tandem fixed cylinder as a reference, we can also affirm that the device produces an average drag reduction of 33% for configuration II and 22% for configuration III.

It is interesting to note that while an upstream wake with weaker vortices found in configuration III helps to reduce the amplitude of response (Figure 4), it has no such effect in reducing drag. On the contrary, it seems that the upstream cylinder fitted with parallel plates experiences a drag reduction as well, generating a wake that reaches the second cylinder with a stronger mean profile. This reduction in the velocity deficit must be incurring a drag penalty on the downstream body. Future investigations with particle-image velocimetry should help to verify this hypothesis.

CONCLUSIONS

Suppression of cross-flow, vortex-induced vibration of a circular cylinder is known to be achieved fitting a pair of parallel plates free to rotate around the cylinder. In the present work we showed that f-t-r parallel plates are also effective at suppressing wake-induced vibration of a pair of cylinder arranged in tandem.

Suppression has been accomplished at a value of the combined mass and damping parameter of 0.014. The maximum drag reduction was about 33% for the configuration in which only the downstream cylinder is fitted with the device.

The present results prove that suppressors based on parallel plates have great potential to suppress VIV and WIV of offshore structures with considerable drag reduction.

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