WAKE STRUCTURES AND DYNAMIC RESPONSE OF ONE AND TWO LONG FLEXIBLE CYLINDERS UNDERGOING VORTEX-INDUCED VIBRATIONS

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ABSTRACT

Laboratory experiments were carried out at the water flume of the Department of Aeronautics at Imperial College London. The experiments were focused on investigating the dynamic response of different riser model configurations subjected to Vortex-Induced (VIV) and Wake-Induced Vibrations (WIV). The water flume allowed the generation of uniform currents and by submerging only the lower 40% of the riser model into water, a stepped current was obtained. A single riser configuration was initially studied. Additionally, a configuration consisting of a tandem arrangement of two riser models aligned with the flow direction, was also tested. The flow structures in the wake of the models for each one of the different configurations were investigated by using Digital Particle Image Velocimetry (DPIV).

1. INTRODUCTION

The vast majority of research efforts in the past have been focused on the study of the vortex-induced vibrations of flexibly mounted rigid bodies, with only one degree of freedom (d.o.f.), the transverse motion. Well known reviews on this topic are Bearman P.W. (1984), Sarpkaya T. (2004) and Williamson C.H.K. et al. (2004). Small differences in the response of rigid cylinders with two degrees of freedom have been found, and many of the features documented for 1 d.o.f. cases are valid (Jeon D. et al. , 2001) and (Jauvtis N. et al. , 2003).

Most of the engineering applications in which VIV is a problem, involve flexible bluff bodies. In real situations engineers frequently find long flexible cylinders responding at high structural vibration modes, rather than flexibly mounted rigid cylinders. In the last years, several research campaigns such as the one reported in Chaplin J.R. et al (2005), Trim A.D. et al. (2005) and Lie H. and Kaasen K.E. (2006) to mention some, have been conducted to investigate VIV under these circumstances. The paradigm of rigid cylinder VIV behaviour being a valid hypothesis to predict the response is still a major concern. Important differences in the dynamic response of flexible bodies arise, due to the intrinsic nature of the body, its capacity to vibrate at high mode numbers, and the complex added mass and hydrodynamic damping distributions while in motion. The response, both in-line and transverse with the flow, and the fluid forces exerted on the body are now mode dependent, adding more complexity to the phenomena. In marine engineering applications it is also common to find situations in which these flexible structures are installed downstream of other bodies, either static or free to vibrate, therefore affected by their wake. For the case of arrangements of two cylinders, research efforts have been mostly directed to investigate the effects produced by the wake of a fixed cylinder on the response of a flexibly mounted rigid one, see Bokaian A. and Geoola F. (1984) and Sumner D. et al. (2005). The variable space resulting from problems of interference between two bodies is considerably larger than the one resulting from single cylinder arrangements, that is why many authors have decided to simplify the problem not allowing the motion of the upstream body even though the most generic and realistic situation needs to look at the interference between the two bodies, when they are flexible and free to vibrate at different modes in all directions, such as in this investigation.

2. EXPERIMENTAL DETAILS

The facility used to perform the experiments was the water channel at the Department of Aeronautics of Imperial College London. It has a cross-section of 0.6x0.75 m with a total length exceeding 8m. The maximum water height can be established up to about 0.65m, and the pumping system is able to generate currents up to 0.75 m/s at the maximum water height.

The set-up (fig. 1) consisted of a supporting structure and a pair of riser models. One of these models (model 1) was instrumented with strain gauges along its length and the other one, was the same but without instrumentation (model 2). The models and their supporting structure were designed and manufactured at the workshop of the Department of Mechanical Engineering of the Universitat Rovira i Virgili in Tarragona. The design of the riser models was based on that proposed by Chaplin J.R. et al (2005) with which the Delta Flume campaign was carried out. The supporting structure was fixed to the water channel and the experiments were performed with a current in the flume.

For the present work, a 1.5m length circular cylinder was made of a 6mm diameter aluminium core with 15mm diameter aluminium diaphragms attached to it with cyanoacrylate glue. Everything was covered with a transparent flexible PVC skin, providing an external diameter of 16mm and an aspect ratio (length/diameter) of about 94. The PVC skin provided a smooth external surface as well as protection for the instrumentation, not allowing the water inside the hollow parts of the riser model. The mass of the instrumented riser (model 1) was 0.362 kg/m and its submerged weight was 2.7 N/m. Model 2 had slightly lower mass because of the absence of instrumentation cables, 0.257 kg/m, and its submerged weight was 2.2 N/m. The flexural stiffness was kept very low (6.04 Nm^2) in both models and the mass ratio (ratio of structural mass to displaced fluid mass) was approximately 1.8 for model 1 and 1.3 for model 2. A detail of both riser models can be seen in figure 2 as installed for one of the wake interference experiments. Table 1 shows the main parameters of the experimental arrangement.

A very stiff aluminium structure was designed to secure the ends of the models (figure 1). The models were attached vertically to the supporting structure through universal joints at both ends, with the possibility of changing the applied top tension through a spring system, therefore allowing changes in the natural frequencies of the models. Everything was installed inside the water flume exposing the lower 40% of the models to the current as in Chaplin J.R. et al (2005), where it was seen that reduced water coverages were enough to excite high modes. A stepped velocity profile acting on the model was obtained with Reynolds numbers varying from about 1400 to 12000. Each run was started from calm water, allowing time enough (a total of 60 seconds per run) to avoid the initial flow transient.

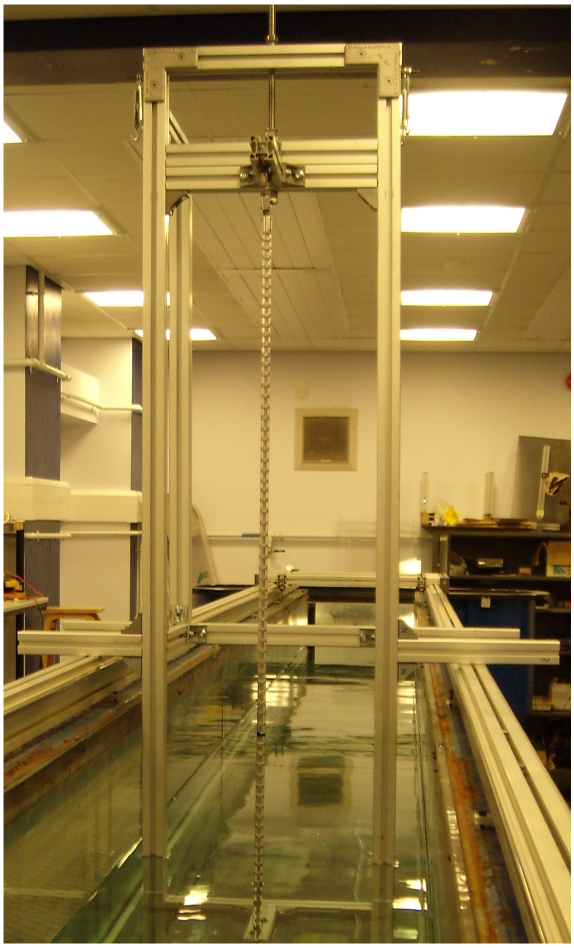


Figure 1: *Set-up (Single riser arrangement).*

As already stated, one of the two existing riser models (model 1) was equipped with 5 strain gauge measurement stations distributed every 0.3 m giving a total of 5 measurement stations. Each one of the measurement stations was formed by 2 half Wheatstone bridges measuring the bending simultaneously in the direction aligned with the flow (in-line), and in the direction transverse to the flow (cross-flow). This instrumentation was suitable for measurements up to the fifth structural mode of vibration, well over the highest expected for the single riser experiments. Strain gauges were found successful in showing the high mode structural response of a long flexible cylinder responding to vortex shedding, in a previous experimental campaign at the Delta Flume in Holland (Chaplin J.R. et al, 2005). To verify that calibrations and the strain gauge measurements were correct, they were compared against independent laser sensor displacement measurements, showing very good agreement.

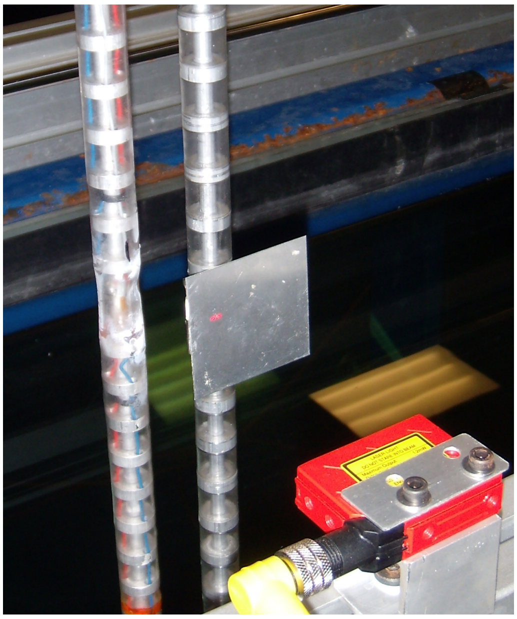


Figure 2: *Set-up (Tandem arrangement).*

Experiment parameters			
External diameter	D	m	0.016
Length	L	m	1.5
Aspect ratio	L/D	-	93.75
Submerged Length	L_s	m	0.585
Flexural Stiffness	EI	Nm^2	6.04
Axial Stiffness	EA	MN^2	1.84
Top Tension	T_t	N	< 110
Flow speeds	V	m/s	< 0.75
Reynolds number	Re	-	1200-12000
Mass	m	kg/m	0.362 | 0.257*
Submerged weight	w_s	N/m	2.7 | 2.2*
Mass ratio	m^*	-	1.8 | 1.3*
Fund. natural freq.	f_1	Hz	2.75-6.10 | 3-7.1*

Table 1: Main parameters (* refers to model 2).

Although one of the two riser models was not instrumented (model 2), when testing both cylinders in tandem configuration, the laser sensor was used to measure the cross-flow displacements at a single point of the upstream body. Hence, for the tandem cases the downstream cylinder was fully instrumented producing data at five points along the axis in both directions, and the upstream one was instrumented with the laser sensor, giving the cross-flow measurement at a point about half the length of the model (figure 2). The two configurations finally tested were:

1. Single riser arrangement (figure 1): The model instrumented with strain gauges was installed in the supporting structure and 5 top tensions (5N, 35N, 60N, 85N and 110N) were tested. For each one of these top tensions the flow speed was varied between 0.1 m/s and 0.75 m/s with increments of 0.05m/s.

2. Tandem arrangement of two risers (figure 2): The model instrumented with strain gauges was installed downstream the model without instrumentation (fig.2), so as to be directly influenced by the wake of the upstream cylinder. Several centre to centre (S) distances were tested: 1.5D, 2D, 2.5D, 3D, 3.5D and 4D. For each S distance 3 top tensions were configured (5N, 60N and 110N) and for each tension the flow speed was varied between 0.1 m/s and 0.75 m/s with increments of 0.05m/s or 0.1m/s. The laser sensor was used to measure the cross-flow displacement at the mid point of the upstream cylinder, at the same height as one of the strain gauge stations in the downstream cylinder (see figure 2).

Digital Particle Image Velocimetry (DPIV) was used to investigate the flow structures in the wake of the single cylinder and the tandem arrangement. A total of more than 500 runs were carried out, producing a very large set of data.

3. RESULTS

3.1. Single riser

Riser excitations in the 1^{st} cross-flow and in-line modes were observed, and in a very few cases the 2^{nd} mode was observed. This was confirmed by computing the modal contributions assuming sinusoidal mode shapes. The maximum non-dimensional cross-flow ($\frac{Y_M}{D}$) and in-line ($\frac{X_M}{D}$) amplitudes along the riser and inside a time window where the response was found to be steady, are plotted in figure 3 against the reduced velocity based on the fundamental natural frequency in water ($V_r = \frac{V}{f_1 D}$). The cross-flow dynamic response in the first mode was found to be very similar to that exhibited by rigid cylinders with 1 or 2 degrees of freedom. In the figure, one can see the initial, the upper and the lower branches of response as reported in Jauvtis N. et al. (2003) but instead of the desynchronisation branch, here the build up of the following mode of the response is observed. It is believed that if higher reduced velocities would have been achieved, the lock-in region of the second mode would have been observed, as reported in Chaplin J.R. et al (2005). The in-line response shows the same behaviour but these branches are not so evident. The maximum cross-flow displacement appears at a reduced velocity inside the range of 6 to 8 with an amplitude of 0.7 diameters. At the same reduced velocities, the in-line amplitudes run up to 0.2 diameters. The ratio of the dominant frequency to the fundamental natural frequency in water was found to be equal to one when running at the first mode in both directions.

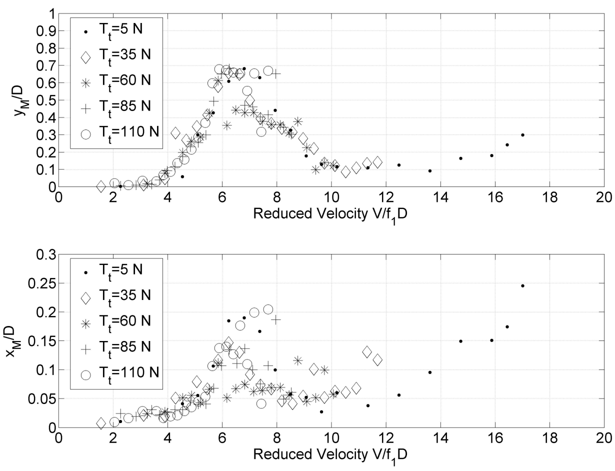
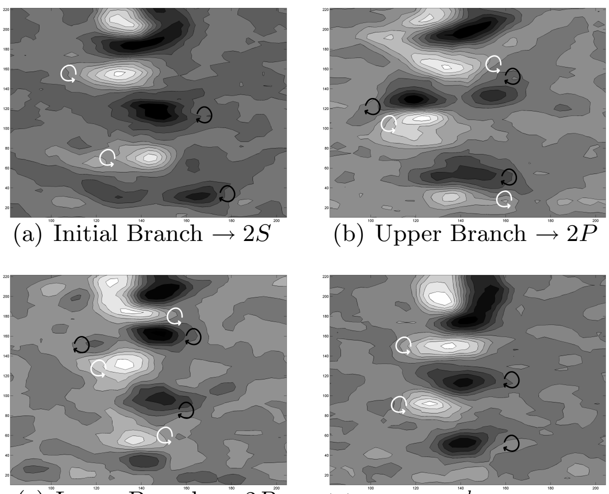


Figure 3: *Non-dimensional cross-flow and in-line Maxima vs. reduced velocity (Single cylinder).*

DPIV images were obtained at planes perpendicular to the axis of the model at two different heights for almost every run, 320mm and 410mm from the bottom end of the model. The intention was to investigate the wake patterns along the submerged part of the riser model. The patterns appearing in the wake of freely vibrating 1 d.o.f. or 2 d.o.f. rigid cylinders are well known as has been reported by several researchers before. It is also well know that for cylinders with variable geometry such as tapered cylinders, the wake patterns can change considerably at different positons over its length (Techet A.H et al. , 1998). This fact might be expected in experiments such as the one presented here because the amplitudes along the length of a long flexible cylinder, vary according to the dominant structural mode shape in the motion. Hence, it was decided to do DPIV interrogations at 2 heights under the free surface.

A first observation of the DPIV data obtained at the lowest plane investigated (320mm), suggests that for all the branches: initial, upper, lower and the built up of the second mode, the vortex structures correspond to the classical vortex street with two single vortices per cycle, referred to by other researchers as the 2S mode. Further investigation in the highest plane implies that the structures are no longer the same as in the lower plane and during some part of the run in some branches, other wake patterns are observed. Figure 4 shows snapshots of the vorticity fields in the wake of the cylinder, situated on the upper part of the image, at the highest plane interrogated, at 410mm from the bottom. The 4 images correspond to each one of the four branches reported. Figure 4(a) is for a test with the highest top tension (110N) inside the initial branch ($V_r = 5.12$) and the 2S mode appears to be dominant. Figure 4(b) reports for a test with also the highest top tension but inside the upper branch ($V_r = 6.14$) and it clearly shows that the width of the wake has changed along with the wake structure, showing now two pairs of vortices at each side of the wake (2P). Figure 4(c) depicts one of the tests run with the top tension set at 60N corresponding to the lower branch ($V_r = 7.79$) and again the 2P mode is observed. Finally, a test performed with the lower top tension in the second mode build-up region ($V_r = 5.12$) is depicted in 4(d), where the 2S mode appears to be the dominant pattern.



(a) Initial Branch $\rightarrow 2S$ (b) Upper Branch $\rightarrow 2P$

(c) Lower Branch $\rightarrow 2P$ (d) Onset 2^{nd} mode $\rightarrow 2S$

Figure 4: Vorticity fields from DPIV measurements for each response branch

3.2. Two risers in tandem

Figures 5 to 7 show the dynamic response measured when the two models where set in a tandem arrangement aligned with the flow with centre to centre distances (S/D) in the range from 1.5 to 4 with increments of half diameter. For each test, the cross-flow maximum displacement ($\frac{Y_M}{D}$) is shown for both the upstream and the downstream riser model as a function of the reduced velocity and the applied top tension.

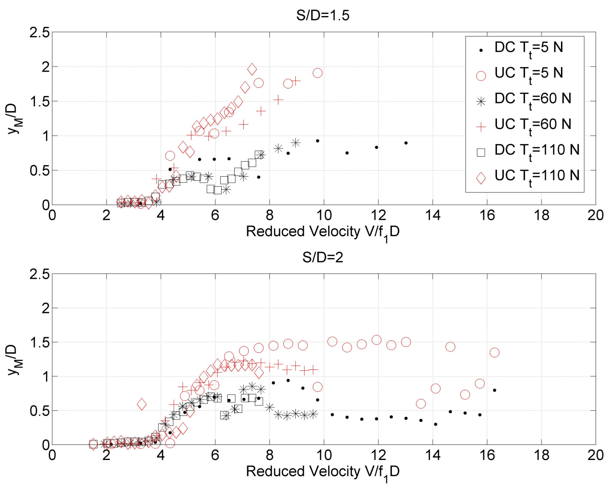


Figure 5: *Non-dimensional cross-flow and in-line maxima of the upstream (UC) and the downstream cylinder (DC) vs. reduced velocity for centre to centre distances of 1.5D and 2D.*

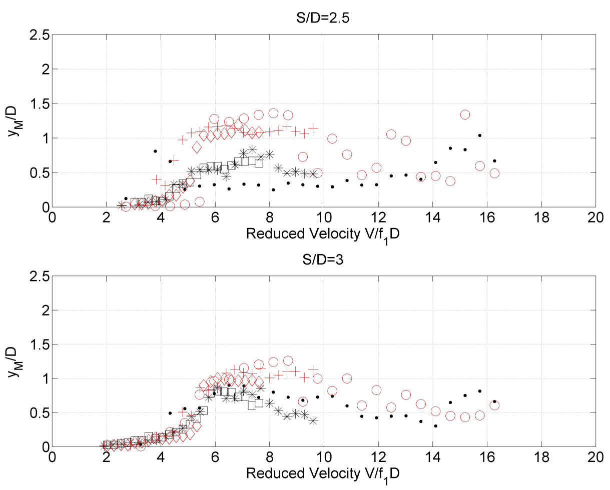


Figure 6: *Non-dimensional cross-flow and in-line maxima of both models in tandem vs. reduced velocity for centre to centre distances of 2.5D and 3D.*

Riser excitations up to the 1^{st} cross-flow and in-line modes have been found with a few cases reporting the 2^{nd} and 3^{rd} mode in the downstream cylinder. A very important observation can be made from all these experiments: the highest displacement is reached by the upstream body for practically all reduced velocities, even though there are three clear "Tandem Response Regimes" (TRR) referring to the reduced velocity axis. The First TRR goes up to $V_r \simeq 4$ for $S/D \leq 3$ and up to $V_r \simeq 5.5$ for $S/D \geq 3.5$, where the motion of both cylinders is very similar with amplitudes lower than 0.25 diameters. In the Second TRR the amplitudes reached by the upstream cylinder are smaller than the ones exhibited by the downstream body. This happens for reduced velocities in the range that goes from about 4 to 4.5 for $S/D = 1.5$, from approximately 4 to 5 for $2 \leq S/D \leq 2.5$ and from 4 to 5.5 (for $3 \leq S/D \leq 4$). The Third TRR is characterized by amplitudes considerably larger in the upstream cylinder than in the downstream one. This is observed when the reduced velocity is larger than 4.5 for $S/D = 1.5$, larger than 5 for $2 \leq S/D \leq 3$ and larger than 5.5 for $S/D \geq 3.5$. Further analysis of the wake through the DPIV data acquired should elucidate possible causes for the large amplitudes of the upstream body.

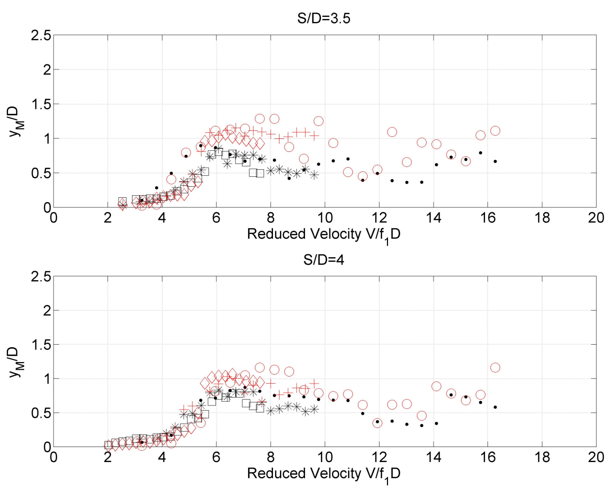


Figure 7: *Non-dimensional cross-flow and in-line maxima of both models in tandem vs. reduced velocity for centre to centre distances of 3.5D and 4D.*

The cross-flow maxima of the upstream cylinder achieves 2 diameters at the smallest $S/D = 1.5$ and gets reduced to about 1 diameter for the largest centre to centre separation $S/D = 4$. The maximum amplitudes of the downstream body are not as dependent on the centre to centre distance as they are for the upstream one, with maxima always about 0.75 - 0.8 diameters. Furthermore, the larger the distance S/D, the more similar the bodies respond because the effect of the wake of the upstream body on the downstream one is weaker.

4. CONCLUSIONS

The response of a single long flexible circular cylinder pin-jointed at its ends responding in its first structural model, is very similar to that exhibited by rigid circular cylinders with 2 degrees of freedom. Wake structures observed are also in accordance with those expected from previous studies but some differences appear according to the plane interrogated along the length of the model, implying that they could be related to the instantaneous shape of the flexible cylinder.

In tandem arrangements the motion of the upstream body cannot be disregarded because it is in fact, practically always larger than the motion of the downstream cylinder. The effect of the modification of the wake and the shear layers when the two bodies interact is crucial not only to understand the motion of the downstream body but also the motion of the upstream one.

Three very clear Tandem Response Regimes (TRR) have been identified in the reduced velocity axis, depending on how the motion of the upstream cylinder relates to the downstream one.

5. ACKNOWLEDGEMENTS

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