UNSTEADY RESPONSE OF A CIRCULAR CYLINDER UNDER WAKE-INDUCED EXCITATION FROM A FIXED UPSTREAM CYLINDER

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ABSTRACT

The present paper discusses the wake-induced vibrations of the downstream cylinder of a tandem pair with separation of 4 diameter from centre to centre. The upstream cylinder is fixed and the downstream one is elastically mounted in a rig with low structural mass and damping which is free to oscillate in the cross-flow direction. Oscillations are observed for reduced velocities as high as 35, reaching levels of amplitude greater than 2 diameters. We believe that wake-induced vibrations are excited by the dynamics of the wake coming from the upstream cylinder rather than the mean velocity profile approaching the downstream cylinder alone. The excitation mechanism has its origin in the lower pressure region induced by the vortices as they approach the downstream cylinder, generating an unsteady force that sustains the vibrations.

1. INTRODUCTION

An elastically mounted cylinder can be excited into flow-induced vibrations if it is positioned within the wake of an upstream bluff body. The wake generated on the upstream body interferes with the downstream cylinder generating fluid forces that can excite the body into high amplitude vibrations. This type of flow-induced excitation mechanism is called *wake-induced vibrations* (WIV) and 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 commonly accommodates more than 40 risers (pipes with relative low mass and damping) in complex arrangements together with many other cylindrical structures. As the ocean current changes its direction down 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 (1990) 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 dynamic of the vortices 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-induce vibrations are sustained. Bokaian and Geoola (1984) present a detailed study of the response of a downstream cylinder in a tandem arrangement and also relates the dependency of WIV on structural parameters such as mass and damping. But it is our objective to analyse the fluid dynamics in the wake that is driving WIV in order to understand the nature of the excitation fluid forces.

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, it is already known that helical strakes typically employed to reduce *vortex-induced vibrations* on an isolated cylinder are no longer effective if the body is immersed in a wake interference region (Korkischko et al. (2007)). In this context, we present an experimental study that is set to support the development of more efficient suppressors.

2. EXPERIMENTAL ARRANGEMENT

Experiments were conducted at the Aeronautics Department of Imperial College, London. A pair of circular cylinders made of rigid Perspex tube was placed in a recirculating water channel with an open test section $0.6m$ wide, $0.7m$ deep and $8.4m$ long. With an external diameter of $D = 50mm$ and a wet-length of $L = 640mm$ (total length below water level, WL) the resulting aspect ratio of the models was approximately 13. The flow speed was continuously variable and good quality flow could be obtained up to at least $0.6m/s$, giving a maximum Reynolds number of approximately $30,000$. The side walls and bottom of the test section were made of glass, allowing a complete view of the models for flow visualization and PIV purposes.

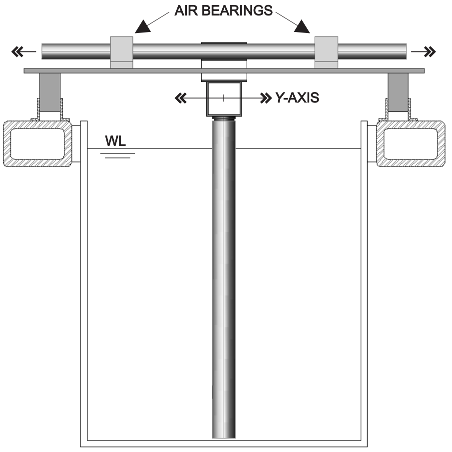

Figure 1: Schematic representation of the downstream cylinder positioned in the test section. The flow is moving perpendicular to the page plane and the cylinder is allowed to oscillate in the transverse direction (*y-axis*).

The upstream cylinder was rigidly attached to the structure of the channel preventing displacements in any direction, while the downstream one was clamped at its upper end to an elastic mounting. Figure 1 shows a schematic representation of the apparatus that only allows the cylinder to displace in the cross-flow direction defined by the *y-axis*. A load cell connects the top end of the cylinder to the rig and is able to measure both instantaneous lift and drag acting on the cylinder.

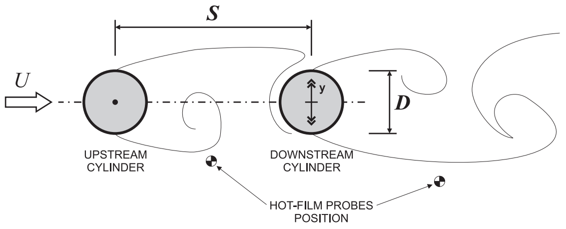

Figure 2: Representation of two circular cylinders aligned in the flow direction (tandem arrangement). The upstream cylinder is fixed and the downstream one is free to oscillate in the transverse direction (*y-axis*).

Both models were aligned in the vertical direction passing through the free surface spanning down the full depth of the section, though the downstream cylinder does not touch the bottom leaving a $2mm$ gap before the glass floor. The restoration force of the system is provided by a pair of tension springs connecting the moving base to fixed supports. Because of the high stiffness of the rig restricting the cylinder to move in the flow direction the present set-up permitted experiments with higher flow speeds - leading to higher reduced velocities - complementing the results presented by Assi et al. (2006) in which a flexing-blade elastic base was employed.

An optical positioning sensor was installed to measure the y-displacement without introducing extra friction to damp the oscillations. As a result, the whole system had a structural damping factor of $\zeta = 0.7\%$, calculated as a percentage of the critical damping obtained from free decay oscillations performed in air. The natural frequency of oscillation in air (f_0) was also determined during the same tests. Repeating the procedure for the immersed body, it is possible to obtain the natural frequency of oscillation in still water (f_w), which takes into account the added fluid mass of the cylinder in still water. 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).

The separation (S) between the two cylinders is measured from the centre of one model to the centre of the other and can be varied up to more than 40 diameters. However, in order to keep a concise analysis, this paper only considers the specific separation of $S/D = 4.0$. A pair of hot-film anemometers was employed to measure velocity fluctuations in two important regions of the flow: in the gap between the cylinders and the developed wake downstream of the second cylinder

(Figure 2). A digital PIV system was also used to map the velocity field around the bodies in order to investigate the flow interference between the bodies.

3. RESULTS AND DISCUSSION

In a previous work (Assi et al. (2007)) we showed that for smaller separations between the cylinders, the downstream body would experience a type of oscillation synchronised with the vortex shedding of the upstream cylinder. This happens because the second cylinder interferes with the shedding mechanism of the first. Even though the upstream cylinder is not oscillating, its shedding is synchronised with the oscillations of the second cylinder within a certain range of flow speed (as in a typical VIV phenomenon). This is a special case of WIV caused by a *Vortex Resonance* in the wake from the upstream flow.

The synchronisation range eventually terminates when the velocity is increased and the upstream cylinder starts to shed vortices as a single fixed cylinder. In the same way, if both cylinders are separated beyond a critical distance (which varies with Re) the oscillations of the second cylinder no longer locks the shedding of the first cylinder and the synchronisation terminates. From this point onwards the downstream cylinder is immersed in a wake that is not synchronised with its own oscillations but the body is excited into even higher amplitudes. This other type of excitation is not associated with any vortex synchronisation and we found it to appear even if the cylinders are separated by 15 diameters or more. The present paper analyses this type of WIV considering a pair of aligned cylinders with separation $S/D = 4.0$.

The dynamic response of the downstream cylinder was investigated over a wide reduced velocity range employing one pair of springs during the whole experiment. The flow speed in the test section was varied in order to cover a reduced velocity range between 2 and 30 resulting in a Reynolds number that varied within the range $1,500 <$Re$< 23,000$ (based on the cylinder diameter and the free stream velocity). The reduced velocity (U/f_0D) presented on the abscissas of all graphs is a non-dimensional value based on the free stream velocity of the flow (U), the natural frequency of oscillation in air (f_0) and the cylinder diameter (D). The amplitude of oscillation (A) is non-dimensionalised by the cylinder diameter (D) and the actual frequency of oscillation (f), by the natural frequency of oscillation in air (f_0). The amplitude of oscillation is defined as the *harmonic amplitude*, obtained from the RMS of the signal times $\sqrt{2}$.

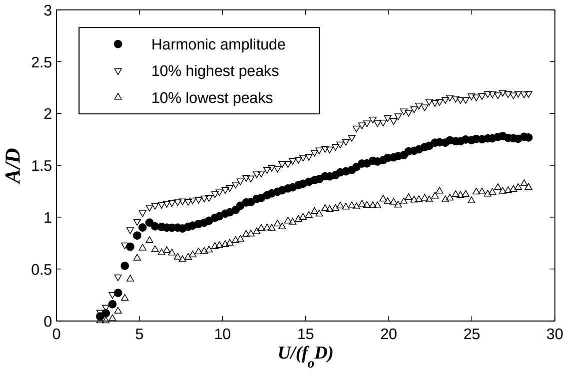

Figure 3: Amplitude of oscillation versus reduced velocity.

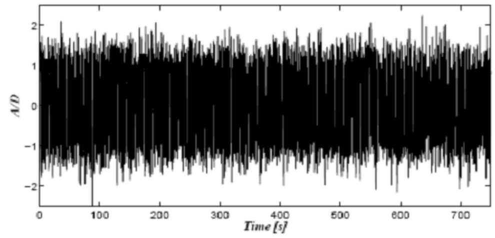

Figure 4: Example of the amplitude time series for reduced velocity 20.0 showing how the envelope of amplitude varies through time.

Figure 3 presents the amplitude of oscillation of the downstream cylinder versus reduced velocity. Back circles stand for the harmonic amplitude described previously while white triangles represent the 10% highest and 10% lowest peaks, giving an idea of the limits between which the amplitude is varying. Unlike typical VIV responses, we found that under WIV the amplitude of oscillation is not constant through time, but the envelope of the signal presents significant variations from peak to peak. Following the points in the graph we notice how the difference between the highest and lowest peaks increases for higher reduced velocities. In Figure 4 we show an example of the amplitude time series at reduced velocity 20.0. Although Figure 3 indicates a harmonic amplitude $A/D = 1.56$ for $U/f_0D = 20.0$ we can clearly notice peaks varying between 1.0 and 2.0 diameters.

The small local peak around reduced velocity 5.0 in Figure 3is due to the first vortex shedding

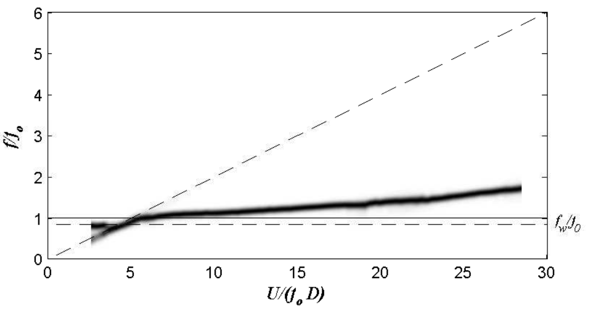

Figure 5: Spectra of frequency of oscillations for the downstream cylinder.

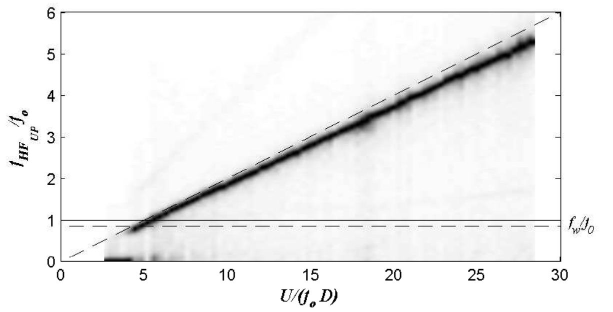

Figure 6: Spectra of velocity fluctuation in the gap flow between the two cylinders.

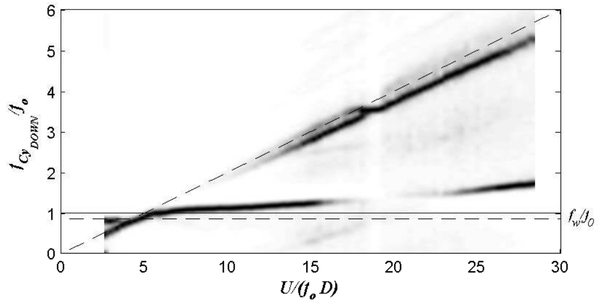

Figure 7: Spectra of the lift acting on the downstream cylinder.

resonance with the natural frequency of oscillation. Other small local peaks are expected to appear when the upstream shedding frequency matches an integer multiple of the natural frequency of the second cylinder, creating harmonic amplifications of the amplitude regularly spaced throughout the velocity range. After this first peak the amplitude of oscillation builds up and high amplitude oscillations remain indefinitely for higher reduced velocities characterising the typical oscillation response of wake-induced excitation.

Figures 5, 6 and 7 represent a compilation of frequency spectra, each one calculated for a separate experimental run at a particular value of reduced velocity. The two axes correspond to the reduced velocity and the normalised frequency in question, while the power spectral density is represented by the intensity of colour. A darker grey spot stands for a higher magnitude power peak in the frequency domain. This process offers more information than only the dominant frequency peak making clear the appearance of bifurcations in the frequency response and showing how the predominant frequency changes from one branch to the other through the reduced velocity range. The horizontal dashed line represents the natural frequency of oscillation in still water (f_w), which is about 85% of the natural frequency of oscillation in air (f_0). The diagonal dashed line represents the theoretical shedding frequency for a Strouhal number of 0.2.

The frequency of oscillation of the downstream cylinder shows a well defined behaviour through the entire range of reduced velocity as observed in Figure 5. The WIV response is clearly dominated by only one frequency branch that departs from $f/f_0 = 1.0$ in a roughly linear ramp almost reaching $f/f_0 = 2.0$ for the highest reduced velocity. This is different from a typical VIV response for a single cylinder, in which the frequency would follow the Strouhal law after the synchronisation regime, the wake-induced excitation shows low frequency oscillations for reduced velocities as high as 20.

We say that WIV presents relatively low frequency oscillations when it is compared with the shedding frequency coming from the upstream cylinder, which is the other significant frequency observed in the interference problem. Figure 6 shows the frequency spectra of velocity fluctuations obtained with a hot-film anemometer in the gap between the cylinders (see Figure 2. It clearly points out that the upstream cylinder is shedding vortices according to the Strouhal law very close to what is expected for a single fixed cylinder. We know that interference from the downstream one happens when the cylinders are closer to each other, however at $S/D = 4.0$ we cannot notice a lock-in phenomenon or any other influence from the oscillations of the downstream cylinder.

The shedding frequency of the upstream cylinder is expected to be found in the spectra of hydrodynamic forces acting on the second cylinder, since it causes fluctuations in the flow field that is approaching the downstream body. As Figure 7 reveals we can observe this frequency as a clear branch appearing in the lift spectra of the downstream cylinder. Although the lift contains fluctuations at this particular frequency the response of the downstream cylinder has a much lower frequency and is never synchronised with the upstream shedding. This shows that the wake activity coming from the first cylinder is somehow exciting the oscillations of second cylinder but at a different frequency. We find that for specific reduced velocities the upstream shedding frequency matches an integer multiple of the natural frequency causing an amplification of the amplitude response in a type of sub-harmonic resonance. This is happening for reduced velocity 19, resulting in a small local peak in the amplitude curve (Figure 3) and a well defined peak in the lift spectra for the downstream cylinder (Figure 7). However, even for these resonance cases, the downstream cylinder remains oscillating at a much lower frequency, as shown in Figure 5.

The key to understanding the wake-induced excitation is to comprehend the mechanism by which the vortices from the upstream cylinder are driving the second cylinder into high amplitude and low frequency oscillations. We believe that the PIV measurements of the flow field around both cylinders are crucial to reveal the nature of the excitation force. Figure 8 shows an instant of the flow field obtained around reduced velocity 20. Figure 8(a) presents vorticity contours and shows that a fully developed wake is formed between the cylinders, while Figure 8(b) shows the velocity field associated with the vorticity plot.

In both figures we note that the vortices shed from the first cylinder can either find a path close to the second cylinder (when it is displaced at higher amplitudes) or impinge on the downstream body if it is close to the centreline of the wake. Either way, the vortices shed from one side of the upstream cylinder induce a flow with higher velocity on the opposite side of the downstream cylinder when it is crossing the wake. A close look on Figure 8 clearly shows that the vortex approaching the downstream cylinder in image (a) induces a stream of high velocity flow on the left-hand side of the downstream cylinder, represented by the brighter grey colour and velocity vectors on image (b). This high velocity stream results in an area of lower pressure on the left-hand side pushing the cylinder back to the centreline of the wake, therefore generating the lift force that excites the vibrations in a type of wake buffeting phenomenon.

At this point one might argue that this force towards the centreline is restoring the cylinder to its original position and could not excite any vibration. But, because of the low-mass and damping characteristics of this system, only a minute phase lag between the displacement and the force is required to excite high-amplitude vibrations. We believe this minimum phase delay is probably generated when the wake shifts from one side to the other as the cylinder crosses the centreline.

Another observation that is consistent with the proposed explanation is the variation of the amplitude from one cycle to another, exemplified in Figure 4. Because the upstream wake has a shedding frequency that is not synchronised with the oscillations, the cylinder may find vortices with different intensities and in different positions as it crosses the wake, inducing forces with varying magnitude from cycle to cycle. Also, the cylinder crosses the wake with considerable transverse speed transferring momentum to the wake (that may cause it to deflect), interacting with vortices and affecting the dynamics it will encounter in the following cycle. All these mechanisms can disturb the wake changing the excitation intensity the cylinder receives each time it crosses the wake.

The present study also supports that the excitation is directly related to the intensity of the vortices in the wake. Every experiment on tandem cylinders has shown that the wake-induced vibration is minimised for larger separations between the cylinders, up to the limiting case after which the body will respond as an isolated cylinder. This observation is also in accordance with our theory, since the vortices would have more time to dissipate and diffuse before reaching the downstream cylinder, resulting in a less intense excitation. For the same reason, we believe that the amplitude of oscillations should be a function of Reynolds number, since it governs the intensity of the vortices in the wake.

4. CONCLUSIONS

We propose that wake-induced vibrations are excited by the dynamics of the wake coming from the upstream cylinder rather than the mean velocity profile approaching the downstream cylinder alone. Unlike the wake-galloping mechanism that excites an elastically mounted cylinder in a staggered arrangement, the vortices impinging on the second cylinder are essential to drive high amplitude, low frequency oscillations.

We verified that for a separation of 4 diameters from centre to centre the oscillations of the downstream body do not interfere with the shedding mechanism of the upstream cylinder for $1,500 < Re < 23,000$ and the upstream cylinder is shedding vortices as an isolated fixed cylinder, very close to Strouhal number 0.2.

The excitation mechanism has its origin in the lower pressure region induced by the vortices as they approach the downstream cylinder. This buffeting force acts pushing the cylinder towards the centreline of the wake, but only a small phase lag between the displacement and the lift is needed to input energy into the system and excite a cylinder with low mass and damping into severe wake-induce vibrations.

5. ACKNOWLEDGEMENTS

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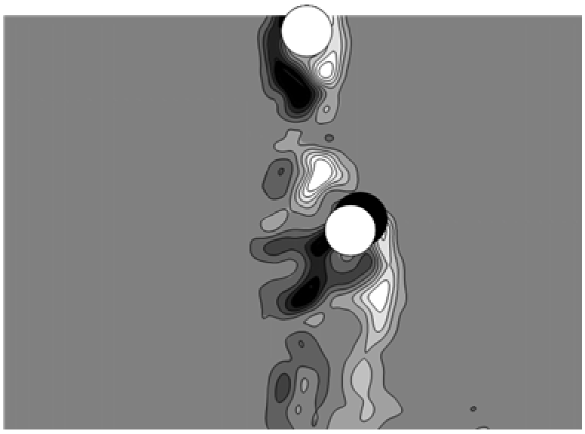
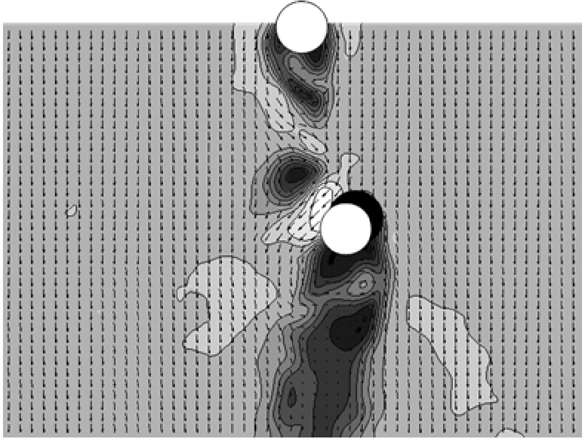


(a) Vorticity contours. The grey scale represents positive and negative vorticity.



(b) Velocity magnitude. Magnitude increases as the grey scale varies from black to white.

Figure 8: Example of vortex interaction when the downstream cylinder is moving to the right. Flow field obtained with PIV.