THE CROSS-FLOW OVER A PAIR OF STAGGERED CYLINDERS

Stuart J. Price*, Michael P. Païdoussis* and Srikanth Krishnamoorthy**
*Department of Mechanical Engineering, McGill University, Montreal, Québec, H3A 2K6, Canada
**National Aerospace Laboratories, Bangalore, India

Summary An experimental investigation is presented for the cross-flow over a pair of staggered circular cylinders, with the upstream cylinder subject to forced harmonic oscillation transverse to the flow direction. Flow-visualization of the wake-formation region and spectra from hot-film measurements in the wake are reported. Two distinct types of wake synchronization are identified, where either the shear-layer shedding frequency or the frequency of the combined wake synchronize with the oscillation frequency.

Introduction

The cross-flow over pairs of closely spaced circular cylinders has proven to be very rich in terms of the resulting fluid dynamic phenomena; see, for example, the work of Sumner *et al*. [1] where, depending on the geometric configuration of the cylinders, three broad categories of flow-interference could be identified; these could be further sub-divided into nine different flow patterns involving processes of shear layer reattachment, induced separation, vortex pairing and synchronization, and vortex impingement. This flow becomes even more complex when one of the cylinders is either allowed to vibrate freely or oscillates in forced motion. For one particular geometric configuration, where the downstream cylinder inhibited the formation of vortices from the upstream cylinder, the authors [2] recently demonstrated that oscillating the upstream cylinder causes considerable differences in the flow structure compared with when the cylinders are held fixed. In addition, depending on the frequency of oscillation, sub- and super-harmonic resonances are obtained between the vortex formation frequency and the cylinder oscillation frequency.

In the present paper the near-wake flow structure around a pair of cylinders with $L/D = 2.0$ and $T/D_{mean} = 1.0$ is discussed; the upstream cylinder oscillates with peak-to-peak amplitude of $0.44D$, hence, the range of T/D is from 0.78 to 1.22. For stationary cylinders, Sumner *et al.* [1] suggest that this flow belongs to the *gap vortex pairing, splitting and enveloping* (VPSE) regime for $T/D > 1.0$, while for $T/D < 1.0$ it belongs to the *gap vortex pairing and enveloping* (VPE) regime. Both of these flow regimes demonstrate a strong synchronization between the shear layers shed on either side of the gap flow between the cylinders, which combine to form a pair of vortices. In addition, there is enveloping of this vortex pair by the outer shear layer shed from the upstream cylinder. The main difference between the VPE and VPSE regimes is that for the VPE regime the enveloping is complete, leading to a wake with two rows of vortices downstream of the cylinder pair, while for the VPSE regime the enveloping is incomplete. A second characteristic of both these flow regimes is that the wake contains two dominant periodicities with distinct Strouhal numbers.

Experimental Procedure

Experiments were conducted in a closed-circuit water tunnel. The downstream cylinder was held fixed in place, while the upstream cylinder was oscillated harmonically and transverse to the flow direction with constant amplitude of oscillation of $0.44D$ peak-to-peak. The frequency of oscillation, f_e, was varied in the range $0.04 < f_eD/U < 0.43$; the two Strouhal numbers mentioned in the foregoing are within this range of nondimensional frequency. In the course of the experiments the flow velocity was such that the Reynolds number, $\mathrm{Re} = UD/\nu$, was kept approximately constant in the range $1440 < \mathrm{Re} < 1680$. The wake-formation region was visualized using Rhodamine dye injected from the surface of either one or both of the cylinders; this was then illuminated via a xenon arc lamp and recorded using a S-VHS video camera. Hot-film measurements of the wake spectra were undertaken concurrently with the flow-visualization experiments; to fully investigate the wake behaviour, these measurements were taken at a number of different locations in the wake.

Results and Conclusions

Flow visualization and hot-film measurements, conducted with both cylinders held fixed in place, confirmed the existence of two Strouhal numbers for this configuration and suggested that the higher of the two Strouhal numbers (between 0.37 and 0.41 as T/D varied from 1.22 to 0.78, respectively) corresponded to the frequency at which the four shear layers were shed from the cylinders, while the lower Strouhal number (0.13 for $0.78 < T/D < 1.22$) corresponded to the dominant frequency associated with the combined wake of the two cylinders. This conclusion is a little contradictory to that of Sumner *et al.* [1] who suggested that the shear layers were shed at different frequencies.

Bearing in mind that the wake contains two dominant periodicities, it is expected that oscillating the upstream cylinder will cause some degree of synchronization with both of these periodicities. This is what was observed, and two distinct types of wake synchronization were identified. This led to considerable difficulty in interpreting the results, and it was only by considering both the hot-film measurements and the flow visualization simultaneously that a successful interpretation of the wake was obtained. Ultimately, it was shown that the shedding frequency from the shear layers synchronized with either f_e or $f_e/3$, and in addition the combined vortex street frequency synchronized with f_e or $f_e/2$.

One of the four sets of wake spectra, measured at different wake positions, is shown in Figure 1. It is immediately apparent that there is a fundamental lock-in between the wake periodicity and the cylinder oscillation for $0.12 < f_eD/U < 0.29$. However, regions of wake synchronization at $f_e/3$ for $0.14 < f_eD/U < 0.15$ and $f_e/2$ for $0.17 < f_eD/U < 0.18$ are also apparent (the relative strength of these different lock-in regions varied depending on the positions at which the measurements were made). As previously mentioned, it is only by examining the wake spectra simultaneously with the flow visualization that the exact form of the synchronization could be determined. Two typical flow visualization images, obtained at different times during a cycle of oscillation with $f_e/DU = 0.190$ are shown in Figure 2. Both of these images show the characteristic narrow wake behind the upstream cylinder and wide wake behind the downstream one; also clearly evident is the enveloping or partial enveloping of the wake by the shear layer shed from the outer surface of the upstream cylinder. Also apparent from the flow visualization videos is the strong coupling between the cylinder oscillation frequency and either the shear layers, or in the particular case shown in Figure 2, the combined wake.

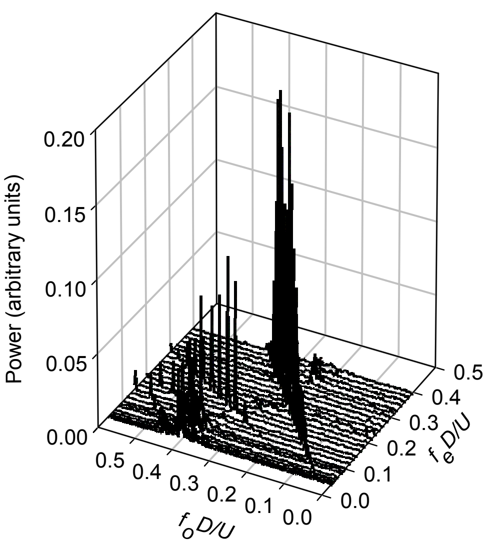

Figure 1. Three-dimensional representation of wake power spectra as a function of the excitation frequency, f_e.

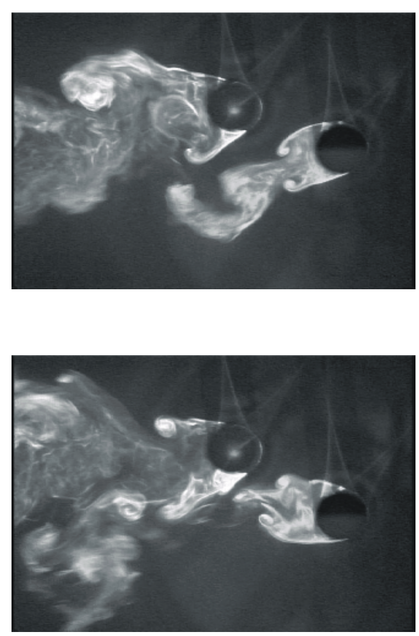

Figure 2. Flow visualization of images during fundamental lock-in with the upstream cylinder oscillating at $f_e/DU = 0.190$.

References

[1] Sumner, D., Price, S.J. & Païdoussis, M.P. 2000 Flow-pattern identification for two staggered circular cylinders in cross-flow. *Journal of Fluid Mechanics* 411, 263-30.

[2] Price S.J., Krishnamoorthy, S. & Païdoussis, M.P. 2002 Cross-flow past a pair of staggered cylinders with the upstream cylinder subjected to a transverse harmonic oscillation. In proceedings of *ASME International Mechanical Engineering Congress,* New Orleans, paper IMECE2002-32181.