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INTERFERENCE BETWEEN TWO CYLINDERS IN A UNIFORM STREAM

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Abstract

The flow field and structural vibrations of two side-by-side cylinders in a uniform cross flow were measured simultaneously in an effort to understand the interference effects of such a flow configuration. A single hot-wire was used to measure the velocity field, while the lateral structural responses were measured on one cylinder only using an optical fibre Bragg grating (FBG) sensor and a laser vibrometer. These measurements were compared with those obtained for a single cylinder. It was found that the fluctuating bending displacement Y measured by the laser vibrometer, when small, is linearly related to the axial strain ε obtained by the FBG sensor. As the cylinder spacing decreases, the strain-displacement relationship remains linear, but the slope changes as a result of interference between the cylinders. When the spacing is reduced to 1.13 cylinder diameter, the two cylinders act like a single structure. Furthermore, a prominent peak in the rms values of ε and Y occurs near the reduced velocity $U_r \approx 10$; tripling the peak values measured at $U_r \approx 5$. This could be attributed to the combined effects of resonance and interference between the cylinders.

1. Introduction

Interference between circular cylinders placed side-by-side in a cross flow has attracted considerable interest among researchers because of its fundamental importance and practical significance in engineering. Earlier work was reviewed by Zdravkovich (1977). The interference drag measurements for two side-by-side cylinders facing the wind traced back to Biermann & Herrnstein (1933). Zdravkovich and Pridden (1977) measured the lift coefficient as well as the drag coefficient, and noted that the sum of the low and high drag generated by the two cylinders respectively was always less than twice the drag of a single cylinder. Using a photographic method, Landweber (1942) observed a single vortex street for $T/d \leq 1.5$ (where T is the transverse spacing between cylinders and d is the diameter of the cylinders), and two distinct streets for $T/d > 2$. Spivack (1946) found two different frequencies in the wakes for $T/d < 2$ but a single frequency for $T/d > 2$, which was the same as the single cylinder wake. Using Schlieren optical method, Ishigai *et al.* (1972) visualised the flow behind two side-by-side cylinders. They noted a markedly symmetric vortex formation and shedding for T/d = 2.5 and 3.0, and a biased gap flow when T/d was between 1.25 and 2.0. The biased flow was bistable and intermittently changed over from one side to another. Bearman and Wadcock (1973) conducted simultaneous measurements of the base pressures on both cylinders and confirmed the bistable nature of the biased flow pattern. Williamson (1985) carried out a detailed study of flow patterns using flow-visualisation methods. Numerical simulation has also been attempted in the regime of low Reynolds numbers (e.g. Slaouti & Stansby, 1992). In spite of these efforts, our understanding of the fluid-structure and structure-structure interactions is still lacking.

The present work aims to examine experimentally the interference between two side-by-side cylinders in a cross flow. Simultaneous measurements of the flow field and structural vibrations were carried out. The flow field was measured by a single hot-wire, the lateral structural responses were obtained on one cylinder only using an optical fibre Bragg grating (FBG) sensor and a laser vibrometer simultaneously. The laser vibrometer (Trethewey *et al.* 1993) is non-intrusive, and has generally been used to measure vibrations in a stationary medium (no flow). Ching et al. (1998) demonstrated that the technique could be used to measure reliably the bending displacement due to the fluctuating lift on a bluff body in a cross flow. The FBG sensors (Kersey *et al.* 1997) have been extensively used in telecommunications, instrumentation and sensors for the measurement of strain, temperature and hydrostatic pressure. Zhou *et al.* (1998) have successfully applied the FBG sensor for the measurement of the axial fluctuating strain on a circular cylinder in a cross flow and showed an excellent agreement, in terms of the spectra of structural response signals, between the FBG sensor and the laser vibrometer measurements. Their measurements showed basis against which to compare interference between the cylinder.

2. Experimental Details

Experiments were conducted in a suction-type wind tunnel with a square cross-section (0.35m x 0.35m) that is 0.5 m long. Two acrylic circular cylinders (d = 0.006m) were vertically mounted, with fixed support at both ends, in a side-by-side arrangement and symmetrically placed at the mid-plane of the working section, 0.20m from the exit plane of the contraction. This resulted in a blockage of about 3.4% and an aspect ratio of 58. Three transverse spacing ratios, T/d = 1.13, 1.70 and 3.00, were tested. These ratios were representative of the different flow regimes for two side-by-side cylinders (Zdravkovich, 1985). The Reynolds number $Re = U_\infty d/\nu$ investigated varied from 800 to 7600, where U_∞ is the free stream velocity and ν the fluid kinematic viscosity.

In the free stream, the streamwise turbulence intensity was about 0.2%.

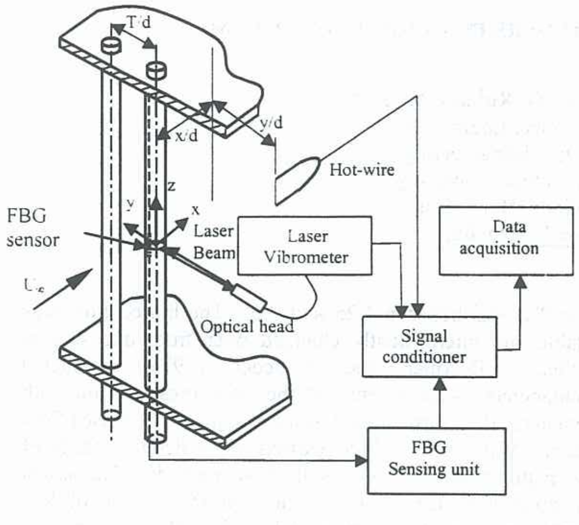

Figure 1 Experimental setup

The experimental arrangement is shown schematically in Figure 1. The streamwise fluctuating velocity u was measured by a single Tungsten hot-wire located at x/d = 2 (x is the streamwise distance downstream of the cylinder centre) and y/d = 1.5. The hot-wire was operated at an overheat ratio of 1.8 with a constant temperature anemometer (DISA Type 55M10). One optical silica fibre of diameter 125 μm built with an FBG sensor was bonded using nail polish along the cylinder span at 90° from the leading stagnation line and flush with the surface. The sensor located at the mid-span of the cylinder measured the axial strain ε associated with the lateral bending displacement (note that the streamwise displacement does not result in strain at the point where the FBG sensor is located). Several types of measurements (Zhou *et al.* 1998) indicated a negligible effect of the attachment of the optical fibre on the flow separation around the cylinder and the structural vibration characteristics. The FBG sensing system was built in-house; details are given by Jin *et al.* (1998). A Polytec Series 3000 Dual Laser Beam Vibrometer was employed to measure the lateral bending displacement Y at the mid span of the cylinder. While one laser beam measured the displacement at the point where the FBG sensor was attached, the other monitored the tunnel vibration at the same cross-section. The differential signal Y from the two beams grossly reduced the contamination from the tunnel vibration to the displacement measurement. The signals Y, ε and u were simultaneously offset, amplified and then digitized using a 12bit A/D board and one personal computer at a sampling frequency of 3.5 kHz per channel. The duration of each record was about 15 s.

3. Results and discussions

Figure 2 presents the typical spectra of the ε, Y and u signals at Re ≈ 6000 for three different T/d. At T/d = 3.0, the spectra (Fig. 2a) are quite similar to those reported by Zhou et al. (1998) in a single cylinder case. This is reasonable since the interference between the cylinders is small.

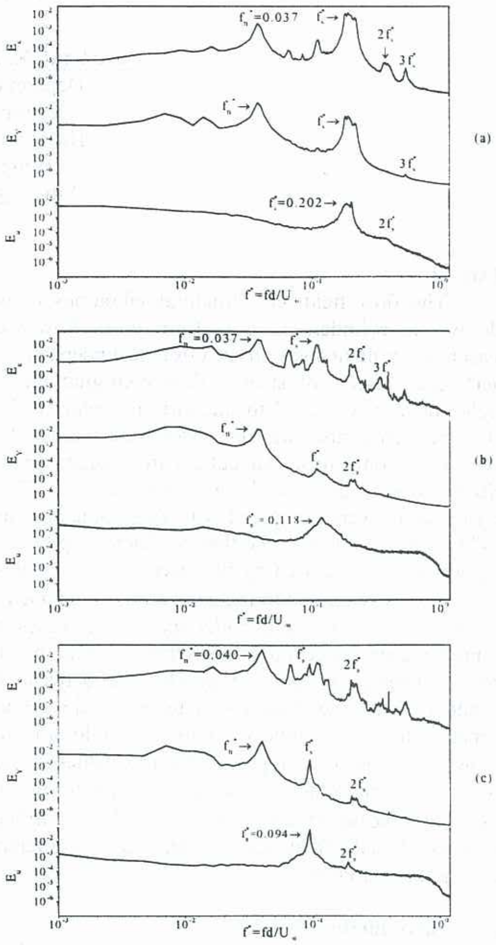

Figure 2 Power spectra E_ε of the strain ε due to lift, E_Y of the lateral bending displacement Y, and E_u of the streamwise velocity u. (a) T/d = 3.0, Re = 6040; (b) T/d = 1.7, Re = 6070; (c) T/d = 1.13, Re = 5750. (The hot-wire was located at $x/d = 2$ and $y/d = 1.5$).

In general, there appears a strong resemblance between the ε-spectrum E_ε and the Y-spectrum E_Y in terms of major characteristics; both exhibit two prominent peaks at identical frequencies. One occurs near $f_s^* = f_s d/U_\infty = 0.202$, identical to the vortex shedding frequency as indicated by the u-spectrum E_u. The cylinder was excited at $2f_s^*$ and $3f_s^*$ of f_s^*, as shown by peaks at these frequencies in the spectra. It is evident that the ε measurement is more sensitive to excitations at the higher harmonics of f_s^* than that of Y. The peaks at $2f_s^*$ and $3f_s^*$ are barely visible in E_Y. At T/d = 1.7 (Fig. b), $f_s^* \approx 0.118$ is almost halved compared with that measured at T/d = 3.0. Note that E_u still exhibits a strong and broad peak around f_s^* (c/f Fig. 2a). However, the peaks of E_ε and E_Y are much less prominent. This implies that while the energies, transferred from fluid to the cylinder, associated with the vortex shedding may be comparable as T/d decreases from 3.0 to 1.7, the corresponding vibrations have been weakened significantly. This suggests a substantial increase in energy dissipation because of the interference between the cylinders. As T/d is further reduced to 1.13 (Fig.2c), f_s^* drops to 0.094, in agreement with previous observations (Spivac 1946). The peak at f_s^* appears to be sharper and narrower for E_u and more prominent for E_ε and E_Y. Another prominent peak occurs at $f_n^{'}$ = 99 or $f_n^{'*}$ = 0.037 at Re = 6040. This frequency is consistent with the calculated natural frequency $f_n^{'*}$ (Ching *et al.* 1998) of the combined fluid-structure system of a single cylinder.

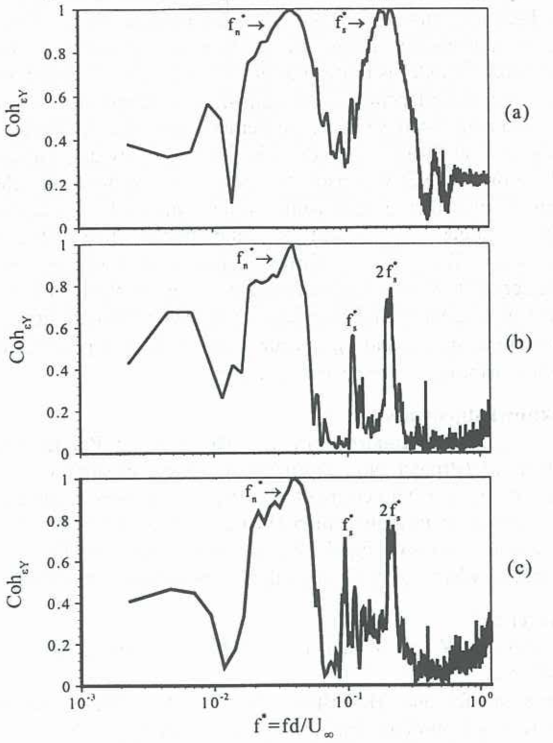

Figure 3 Spectral coherence $Coh_{\varepsilon Y}$ between the strain ε due to lift and the lateral bending displacement Y. (a) T/d = 3.0, Re = 6040; (b) T/d = 1.7, Re = 6070; (c) T/d = 1.13, Re = 5750

The spectral coherence $Coh_{\varepsilon Y}$ = $(Co^2_{\varepsilon Y} + Q^2_{\varepsilon Y})/E_\varepsilon E_Y$, where $Co_{\varepsilon Y}$ and $Q_{\varepsilon Y}$ are the cospectrum and quadrature spectrum of ε and Y, respectively, provides a .measure of the degree of correlation between the Fourier components of the fluctuations ε and Y. At T/d = 3.0, $Coh_{\varepsilon Y}$ (Fig. 3a) reaches 1 around both f_s^* and $f_n^{'*}$, i.e. a near perfect correlation between ε and Y signals at these frequencies. As T/d decreases, $Coh_{\varepsilon Y}$ (Fig. 3b and 3c) remains almost 1 at $f_n^{'*}$, but drops appreciably at f_s^*. From the point of view of structural dynamics, ε and Y tend to be correlated for the odd vibration modes of the cylinder and de-correlated for the even modes. It is likely that the enhanced interference between the cylinders, as T/d reduces, results in a sophisticated mixture of vibration modes, which is responsible for the decline in $Coh_{\varepsilon Y}$.

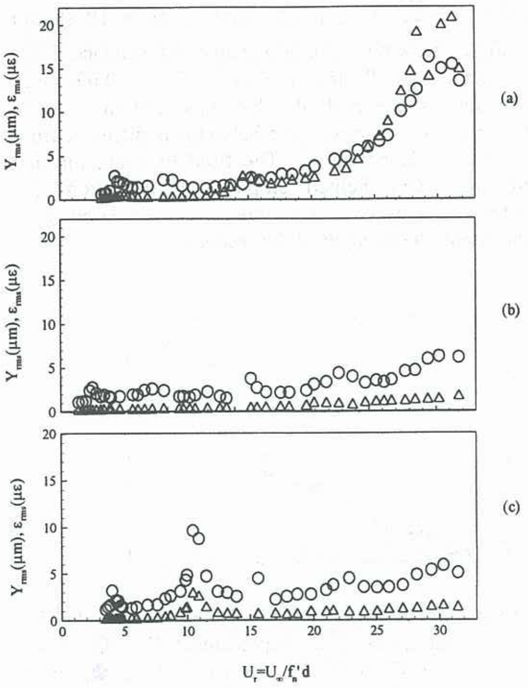

Figure 4 Dependence on the reduced velocity $U_r = U_\infty / f_n^{'} d$ of the rms values of the strain ε_{rms} (Δ) and the bending displacement Y_{rms} (O). (a) T/d = 3.0; (b) T/d = 1.7; (c) T/d = 1.13.

Figure 4 presents the variations of the root mean square value Y_{rms} of Y and ε_{rms} of ε with the reduced velocity $U_r = U_\infty / f_n^{'} d$. The accuracy of Y_{rms} is mainly affected by the tunnel vibration noise. This noise has been immensely reduced through the use of the differential signal of the laser vibrometer; the remaining effect is estimated to be minimum. The uncertainty in Y_{rms} is estimated to be no more than 10%. The experimental uncertainty in ε_{rms} is higher, estimated to be 16%. A major contribution to error comes from the non-linearity effect when calibrating the relation between the output voltage V and ε (Zhou *et al.* 1998). The resolutions of the FBG sensing unit and the laser vibrometer are about $0.5\mu\varepsilon$ and $2\mu m$, respectively.

The variations of Y_{rms} and ε_{rms} show a similar trend, both increasing as U_r increases. For all transverse spacing ratios, Y_{rms} displays a peak, reaching about 3μm, at $U_r \approx 5$, where resonance, with f_s approaching $f_n^{'}$, occurs. A local peak is also identifiable at $U_r \approx 15$ for both ε_{rms} and Y_{rms}. This is probably due to excitation at the third harmonic of $f_n^{'}$. Note that, when T/d = 1.13, both Y_{rms} and ε_{rms} (Fig. 4c) exhibit a very prominent peak at $U_r \approx 10$, triple that at $U_r \approx 5$ in magnitude, even larger than the amplitude at U_r =30. On the other hand, only a little hump occurs near $U_r \approx 10$ for the larger value of T/d (Fig. 4a & b). Presumably, at T/d = 1.13, the two cylinders act like a single structure; the effective U_r should be really $U_\infty/(f_n^{'}2d)$, that is, $U_r \approx 10$ should actually correspond to the occurrence of resonance. This point can also be illustrated in terms of $f_s^* \approx 0.094$ (Fig. 2c), which is one half of that measured in a single cylinder wake. However, the behavior is different from that of a single structure. The fluid bleeding through them may have helped amplify the vibration; the interference between the cylinders has increased, to a great extent, the strength of the resonance.

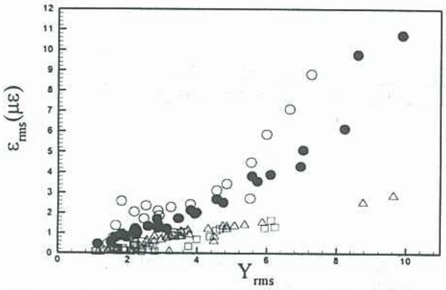

Figure 5 Relationship between the strain ε_{rms} and the lateral bending displacement Y_{rms}. ○, T/d = 3.0; □, T/d =1.7; Δ, T/d = 1.13; ●, single cylinder (Zhou *et al.* 1998).

When $Y_{rms} < 6\mu m$ or $U_r < 25$, the ε_{rms} and Y_{rms} relationship (Fig. 5) is approximately linear. Note that some data ($Y_{rms} < 2$) almost fall on the abscissa due to the insufficient resolution of the FBG sensor when $\varepsilon_{rms} < 0.5\mu\varepsilon$. The T/d = 3.0 data agree reasonably well with those for a single cylinder (Zhou *et al.* 1998). This agreement provides further validation of the FBG sensor technique. When $Y_{rms} > 6\mu m$, the relationship between ε and Y starts to deviate from a linear behavior, probably as a result of the increasing importance of the non-linear vibrations as well as the higher modes of vibrations. As T/d decreases, ε reduces for the same Y. Unlike the single cylinder case (Zhou *et al.* 1998), the relationship between ε and Y appears to vary for different T/d ratios. This could be attributed to a mixture of different vibration modes when interference between the cylinders becomes more and more intense as T/d decreases.

4. Conclusions

Interference between two cylinders in a uniform cross stream has been investigated. The present measurements indicate a significant change, with the variation of T/d, in the vibrational characteristics of the two side-by-side cylinders, consistent with the previous observations of the discontinuities in flow patterns (Williamson 1985). When T/d is sufficiently large, the vibrational behavior of the individual cylinder is quite similar to that of a single cylinder. The strain-displacement relationship is linear for small displacement, in reasonable agreement with the findings of Zhou *et al.* (1998) for a single cylinder, thus providing further validation of the FBG sensor technique. As T/d decreases, the strain-displacement relationship remains linear. However, the slope changes as a result of the interference between cylinders. When T/d is further reduced to 1.13, the two cylinders act like a single structure. Due to the combined effect of resonance and interference between the cylinders, a strong peak in ε_{rms} and Y_{rms} occurs at $U_r \approx 10$, the peak value is about tripling that measured at $U_r \approx 5$.

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