Flow-induced vibrations of two circular cylinders in tandem in a cross flow

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Summary. This study reports on the dynamic response of two elastically-mounted circular cylinders in tandem undergoing transverse flow-induced vibration (FIV) in a free-stream flow. The results show that the FIV responses of the two cylinders are affected significantly by the cylinder-cylinder spacing ratio. This study suggests that there exist a variety of FIV response regimes as a function of the flow reduced velocity and the spacing ratio.

Introduction

The dynamics in flow-induced vibration (FIV) of structures is of substantial continuing interest, due to its intrinsic nature in science and importance in a large variety of engineering applications, such as offshore structures in ocean currents, and high-rise buildings and bridges in winds. In the past six decades, numerous studies have been motivated to fundamentally characterise FIV of bluff bodies and to provide insights into mechanisms of the fluid-structure interaction. This has led to a large body of work with a focus on FIV problems of a single body, e.g. two typical body oscillator phenomena of FIV, *vortex-induced vibration (VIV)* of a circular cylinder and *galloping* of a non-circular cylinder that is susceptible to an aerodynamic instability induced by the body movement (see [1]). On the other hand, considerable studies have also been conducted on flow past two fixed cylinders in tandem (see [2]), and transverse *wake-induced vibration (WIV)* of a free cylinder in the downstream of a fixed cylinder (e.g. [3]). These studies have shown that the spacing between two cylinders in tandem is a key parameter affecting the flow pattern and thus the fluid forcing on the bodies, resulting in complex nonlinear dynamics and structural response. However, much less work has been conducted on the FIV responses of two freely-vibrating cylinders in tandem; this is particularly so for cylinders with low mass ratio (the ratio between the total oscillating mass to the displaced fluid mass) at moderate Reynolds numbers. Thus, this study aims to gain a better understanding of the influence of the cylinder spacing on the FIV responses of two freely-vibrating cylinders in tandem in a free-stream flow, and to analyse the nonlinear dynamics of the fluid-structure interactions and the interaction between the two cylinders, through an experimental investigation of the fluid-structure system with low mass ratio at moderate Reynolds numbers.

Experimental method

The present FIV problem was modelled on two low-friction air-bearing systems (see [4]) in conjunction with the free-surface recirculating water channel of the *Fluids Laboratory for Aeronautical and Industrial Research (FLAIR)*, Monash University. This water channel facility has a test section of $600\,\mathrm{mm}$ in width, $800\,\mathrm{mm}$ in depth and $4000\,\mathrm{mm}$ in length.

The cylinders were vertically mounted onto two separated air-bearing systems. These cylinders, which were precision made from aluminium tubes and anodised against water corrosion, had an outer diameter of $D = 40 \pm 0.010\,\mathrm{mm}$ and an immersed length of $L = 614\,\mathrm{mm}$, giving an aspect ratio of $= L/D \approx 15.4$. For each cylinder, the total oscillating mass was $m = 1473.1\,\mathrm{g}$, and the displaced mass of the fluid was $m_d = 770.3\,\mathrm{g}$, giving a mass ratio of $m^* = m/m_d = 1.91$. The natural frequencies of the two hydro-elastic systems were measured by conducting free decay tests individually in air (f_{na}) and in quiescent water (f_{nw}). The structural damping ratio with consideration of the added masss (m_A) was determined by $\zeta = c/2\sqrt{k(m+m_A)}$, with $m_A = ((f_{\mathrm{na}}/f_{\mathrm{nw}})^2 - 1)\,m$. As shown in table 1, the natural frequencies were almost identical for the two circulars, while the difference in ζ was sufficiently small to have negligible effects. The FIV responses of the two cylinders were investigated for the spacing ratio (denoted by S^* as the streamwise spacing between the cylinder centres, S, normalised by the cylinder diameter, D, namely $S^* = S/D$) ranging from 1.25 to 15.0 over a wide reduced velocity range of $3 \leqslant U^* = U/(f_{\mathrm{nw}}D) \leqslant 30$ and a corresponding Reynolds number range of $1570 \leqslant Re = UD/\nu \leqslant 15\,700$, where U is the free-stream velocity, f_{nw} is the natural frequency in water of the upstream cylinder and ν is the kinematic viscosity. More experimental details can be found in [4].

Results and discussion

Figure 1 shows the normalised amplitude responses as a function of the flow reduced velocity for the two cylinders with various spacing ratios. The amplitude response is denoted by A^*_{10}, which represents the mean of the top 10% amplitude

Cylinder	m [g]	m_{d} [g]	m^*	f_{na} [Hz]	f_{nw} [Hz]	ζ
upstream	1473.1	770.3	1.91	0.432	0.343	2.02×10^{-3}
downstream	1473.1	770.3	1.91	0.430	0.345	1.78×10^{-3}

Table 1: The present experimental parameters of the two (upstream and downstream) cylinders in tandem.

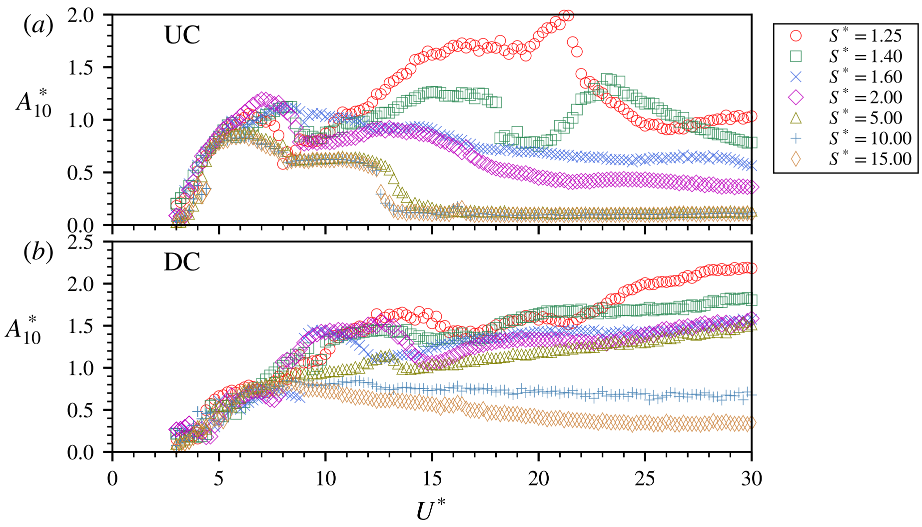

Figure 1: The normalised amplitude responses of the two cylinders in tandem as a function of the reduced velocity for various spacing ratios. The amplitude responses of the upstream and downstream cylinders (UC and DC) are plotted in (a) and (b), respectively.

peaks normalised by D.

As can be seen, the spacing ratio plays an important role affecting the amplitude responses of the two cylinders. For the cases of $S^* \leqslant 2.00$, the vibration of the upstream cylinder (UC) can be significantly enhanced in terms of the peak amplitude and also the U^* range exhibiting large body oscillation amplitude, as compared to that of a typical three-branch VIV response of a single circular cylinder (not shown here). For example, the A^*_{10} response of $S^* = 1.25$ displays an initial branch for low reduced velocities ($U^* < 5$), which is similar to that of the single cylinder case, but as U^* is further increased it exhibits a largely fluctuating variation to reach a peak value of $A^*_{10} \simeq 1.99$ at $U^* = 21.2$ (an increase of 234% against that observed in the VIV upper branch of the single cylinder case), prior to a gradual decrease trend to $A^*_{10} \approx 1.0$ for $U^* > 25$. As S^* is increased to 1.60, after reaching a peak value of $A^*_{10} \simeq 1.12$ at $U^* = 8.0$, the A^*_{10} response shows a gradual decrease trend with increasing U^*, distinctly different from those of the lower S^* cases. As S^* is further increase to 2.0, the A^*_{10} response exhibit a variation profile similar to the typical three-branch VIV response of a single cylinder, but with much larger vibration amplitudes. Furthermore, for the cases of $S^* \geqslant 5.00$, the A^*_{10} responses appear to be highly similar to the single cylinder case, indicating that the upper cylinder vibration is negligibly influenced by the perturbation of the downstream cylinder.

On the other hand, the A^*_{10} response of the downstream cylinder (DC) is also influenced significantly by S^*. As a result of the strong interaction between the two cylinders, the A^*_{10} response of the downstream cylinder tends to increase with U^*, but with large fluctuations at high reduced velocities ($U^* > 7$), for the cases of $S^* \leqslant 2.00$. As S^* is increased to 5.00, the A^*_{10} response sees a fairly stable increase trend for $U^* > 7$. However, for the cases of $S^* \geqslant 10.00$, the A^*_{10} response tends to decrease gradually with U^* increasing beyond 7.

Conclusions

The transverse FIVs of two circular cylinders in tandem have been investigated as a function of U^* for various spacing ratio of $1.25 \leqslant S^* \leqslant 15.00$. It was found that for $S^* \leqslant 2.00$ the FIV responses of the two cylinders exhibit complex variations due to their strong interaction, where their vibration could be largely enhanced as compared to VIV of a single cylinder. Enhancement of the A^*_{10} peak of the upstream cylinder diminished for $S^* \geqslant 5.00$, whereas the downstream cylinder displayed a decrease trend in A^*_{10} with increasing U^* beyond 7 for $S^* \geqslant 10.00$. The present results indicate that there exist a variety of FIV response regimes that would be of great interest for further investigations.

References

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