Flow-induced vibration of a D-shape cylinder

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Summary. This study investigates the dynamic response of transverse flow-induced vibrations of an elastically-mounted D-shape cylinder oriented at two different angles of attack, $\alpha = 0^\circ$ and 180°, in a free-stream. The results show that two typical body oscillator phenomena of FIV, vortex-induced vibration (VIV) and transverse galloping, can occur in different flow regimes for $\alpha = 0^\circ$, while pure VIV response is observed for $\alpha = 180^\circ$ over the flow reduced velocity range investigated ($2 \leqslant U^* \leqslant 12$). This suggests that there exists a transition to a VIV-galloping response with variation of the angle of attack.

Introduction

Flow-induced vibration (FIV) of bluff bodies is an important problem encountered in a large variety of engineering applications, such as oil risers and offshore structures in ocean currents, high-rise buildings and bridges in winds, etc. There are two typical body oscillator phenomena of FIV, vortex-induced vibration (VIV) and galloping, which have motivated extensive research studies that aim to fundamentally characterise and provide insights into the mechanisms. Recent studies by Nemes *et al.* (2012) and Zhao *et al.* (2014) showed that the FIV response of a square cylinder is influenced significantly by variation of the angle of attack, suggesting that the "afterbody" and the flow separations at the sharp corners are the key factors in the mechanisms. Following the previous works, this study aims to provide a better understanding of the influence of the "afterbody" and flow separation locations, by investigating the transverse FIV of a D-shape cylinder with low mass ratio. The following sections will present the experimental method, the results and discussion, and finally the conclusions.

Experimental method

The experiments were conducted in the free-surface recirculating water channel of the Fluids Laboratory for Aeronautical and Industrial Research (FLAIR), Monash University. The test section of the water channel has dimensions of $600\,\mathrm{mm}$ in width, $800\,\mathrm{mm}$ in depth and $4,000\,\mathrm{mm}$ in length. Details of the water channel facilities can be found in Zhao *et al.* (2014).

The rigid D-shape cylinder model used was made from aluminium, using precision electrical discharge machining (EDM) to manufacture a hollow semicircular cross-sectional profile with an outer diameter of $D = 25 \pm 0.010\,\mathrm{mm}$. The cylinder was hard anodised against water corrosion. The immersed length of the cylinder was $L = 614\,\mathrm{mm}$, giving an aspect ratio range of $Æ = L/D = 24.6$. The total oscillating mass was $m = 1113.1\,\mathrm{g}$, and the displaced mass of the fluid was $m_d = 150.1\,\mathrm{g}$, giving a mass ratio of $m^* = m/m_d = 7.39$. The orientation of $\alpha = 0^\circ$ is defined when the flat surface of the cylinder perpendicularly faces the oncoming free-stream, while $\alpha = 180^\circ$ is defined when the flat surface of the body perpendicularly faces downstream. The cylinder was vertically adapted to a low-friction air bearing rig, which was placed atop and transverse to the water channel. More details of this air bearing rig can be found in Zhao *et al.* (2014). The natural frequencies of the system were measured by conducting free decay tests individually in air and in quiescent water. The natural frequencies of the system in air and in water were found to be $f_{N\mathrm{a}} = 0.848\,\mathrm{Hz}$ and $f_{N\mathrm{w}} = 0.810\,\mathrm{Hz}$, respectively, and the structural damping ratio with consideration of the added masss (m_A) was determined by $\zeta = c/2\sqrt{k(m+m_A)} = 3.4 \times 10^{-3}$, in which $m_A = ((f_{N\mathrm{a}}/f_{N\mathrm{w}})^2 - 1)\,m$. The reduced velocity, defined by $U^* = U/(f_{N\mathrm{w}}D)$, was investigated over the range of $2 \leqslant U^* \leqslant 12$, in which U is the free-stream velocity. The corresponding Reynolds number range was $1058 \leqslant Re = UD/\nu \leqslant 6346$, in which ν is the kinematic viscosity.

Results and discussion

Figure 1 shows the amplitude and the frequency responses as a function of the flow reduced velocity for the two angles of attack. The amplitude response is denoted by A^*_{10}, which represents the mean of the top 10% amplitude peaks normalised by D. The frequency response f^* denotes the cylinder oscillation frequency normalised by the system's natural frequency in quiescent water.

For $\alpha = 0^\circ$ in Figure 1 (a), two main flow regimes are observed, which are dominated by VIV for $U^* < 6$ and by transverse galloping for $U^* > 6$. At the low reduced velocity values of $U^* < 3$, the dynamic response of cylinder is characterised by oscillations with extremely low amplitudes ($A^*_{10} \approx 0$) and with the frequency following the trend of the vortex shedding frequency. At $U^* = 3.0$, the cylinder experiences a sudden jump in the oscillation amplitude to $A^*_{10} = 0.23$, and simultaneously the oscillation frequency jumps close to but lower than the natural frequency of the system, indicating that the onset of synchronisation (also known as "lock-in") occurs. In this regime, the body motion exhibits highly periodic oscillations. As the reduced velocity is further increased up to $U^* = 6.0$, the oscillation amplitudes increase rapidly up to $A^*_{10} \approx 1.1$, and meanwhile, the frequency increases slightly up to $f^* \approx 1.1$. These response features slightly differ from

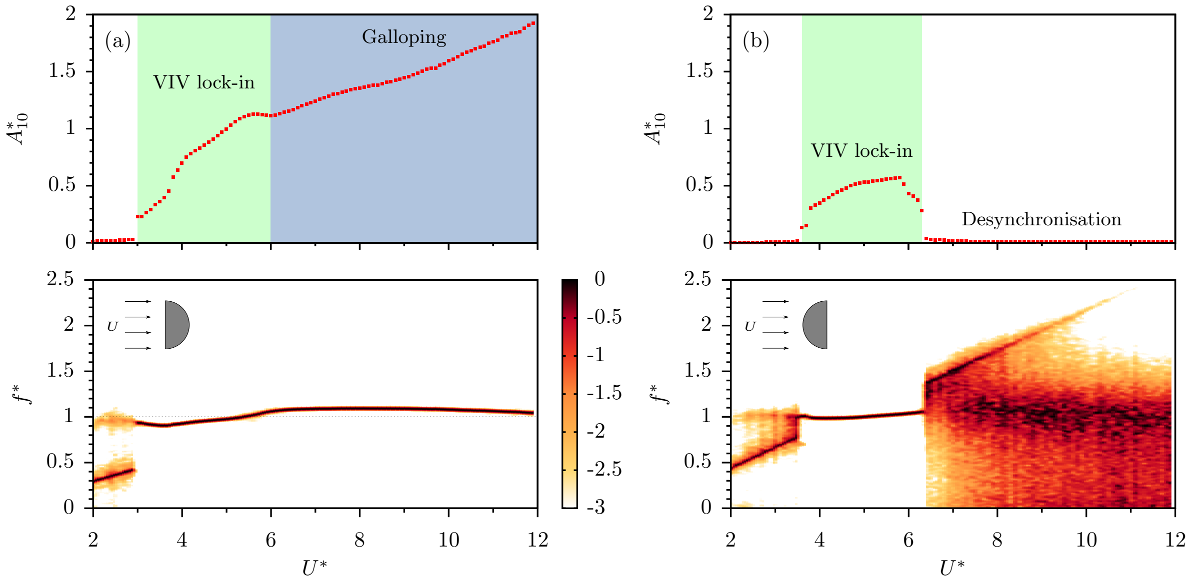

Figure 1: The amplitude response and the logarithmic-scale normalised frequency power spectrum contours of $\alpha = 0°$ in (a) and $\alpha = 180°$ in (b). The regime dominated by VIV lock-in is marked in light green, and the regime dominated by galloping is marked in light blue.

those of classic VIV of a circular cylinder, where the onset of "lock-in" normally occurs at $U^* \approx 5$ when the oscillation frequency locks onto a value equal to or higher than the system's natural frequency, which depends on the mass ratio (see Khalak & Williamson, 1997; Zhao *et al.*, 2014). For higher reduced velocities of $U^* > 6.0$, the body oscillations are fully dominated by galloping, where the amplitude response follows a linear growth trend. However, the oscillation frequency appears to be quite constant for a wide range of U^* prior to a slight decrease towards $f^* \approx 1$; however, it is much higher than that of transverse galloping of a square cylinder reported previously by Bearman *et al.* (1987) and Zhao *et al.* (2014). This difference might be due to the "afterbody" geometry.

For $\alpha = 180°$ in Figure 1 (b), the vibration response in general exhibits pure VIV features. At the low reduced velocities of $U^* < 3.6$, the oscillation amplitudes remain at extremely low values, and the dominant oscillation frequency follows the trend of the vortex shedding frequency. As the reduced velocity is further increased to $U^* = 3.6$, the onset of "lock-in" occurs, and the body oscillations become highly periodic, with the frequency matching the natural frequency of the system, namely $f^* = 1$. The amplitude response experiences a sharp jump to $A^*_{10} = 0.31$ at $U^* = 3.8$. As the reduced velocity is further increased, the amplitude response increases gradually to reach a peak value of $A^*_{10} = 0.57$ at $U^* = 5.8$, prior to a sharp drop which is followed by the desynchronisation region for $U^* \geqslant 6.5$. Compared to the case of a circular cylinder, the peak amplitude of a D-shape cylinder occurs at a similar reduced velocity; however, the peak value of A^*_{10} is $30 - 40\%$ less than that of a circular cylinder, depending on the mass-damping value. Also, the "lock-in" regime appears to be much narrower than that of the circular cylinder case (see Zhao *et al.*, 2014).

Conclusions

The transverse flow-induced vibrations of a D-shape cylinder have been investigated at two different angles of attack, $\alpha = 0°$ and $180°$, over a reduced velocity range of $2 \leqslant U^* \leqslant 12$. At $\alpha = 0°$, the FIV system is dominated by VIV for $U^* < 6.0$, while it becomes gallop-dominated at higher U^* values. At $\alpha = 180°$, the vibration response exhibits pure VIV features; however, the peak amplitude observed, $A^*_{10} = 0.57$, is $30 - 40\%$ less than that for a circular cylinder. Compared to the case of a circular cylinder, the "lock-in" regime is much narrower. The present results indicate that there exists a transition to a VIV-galloping response with variation of the angle of attack.

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