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Fluid forces acting on a cylinder undergoing streamwise vortex-induced vibrations

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A R T I C L E I N F O

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A B S T R A C T

This brief communication examines the fluid forces acting on a cylinder free to move in the streamwise direction throughout its response regime. The amplitude and phase of the unsteady drag coefficient are estimated from the displacement signals and a simple harmonic oscillator model. We examine the counter-intuitive reduction in vibration amplitude observed in streamwise vortex-induced vibrations (VIV) at resonance, which has remained one of the most poorly understood aspects of VIV. Our results show that it is not caused by a change in the phase of the fluid forcing with respect to the cylinder displacement, as suggested by previous researchers; instead, we show that there is a sudden decrease in the amplitude of the unsteady drag coefficient in this region. The possible cause of this result, relating to three-dimensionality in the wake, is briefly discussed.

1. Introduction

The problem of Vortex-Induced Vibration (VIV) of circular cylinders in crossflow is relevant to a wide range of industrial structures, such as tall chimneys, bridges, heat exchangers, off-shore platforms and oil risers. It is a classical fluid–structure interaction problem; the vortices shed from the cylinder induce unsteady fluid forces, which cause the structure to vibrate; this motion in turn affects the wake and the vortex-induced forces. This results in a complex feedback loop between the flow field and the structure that is controlled by the fluid forces. When the predicted vortex-shedding frequency (the Strouhal frequency), $f_{St} = St\,U_0/D$ (where St is the Strouhal number, U_0 is the freestream velocity and D is the cylinder diameter) is close to the vibration frequency of the cylinder, f_x, the cylinder motion can cause the vortex-shedding to occur at f_x or a sub-harmonic instead of the Strouhal frequency, a phenomenon known as 'lock-in'.

The structural response, wake mode and the presence of lock-in are controlled by the so-called 'true' reduced velocity (Cagney and Balabani, 2013c; Govardhan and Williamson, 2000; Aguirre, 1977), $U_r St/f^*$, where $U_r = U_0/f_n D$ is the conventional reduced velocity, f_n is the natural frequency measured in a still fluid, and $f^* = f_x/f_n$ is the frequency ratio. The 'true' reduced velocity (henceforth referred to simply as the reduced velocity) is equal to the ratio of the predicted shedding frequency to the actual response frequency, f_{St}/f_x. As the fluctuating drag occurs at twice the shedding frequency, lock-in is expected to occur in the streamwise direction (i.e. parallel to the flow) at $U_r St/f^* = 0.5$, and at $U_r St/f^* = 1$ in the transverse direction (i.e. normal to the flow). This is typically associated with a change in the arrangement of vortices in the wake (the 'wake mode') and an increase in the vibration amplitude, A (Williamson and Roshko, 1988; Morse and Williamson, 2009).

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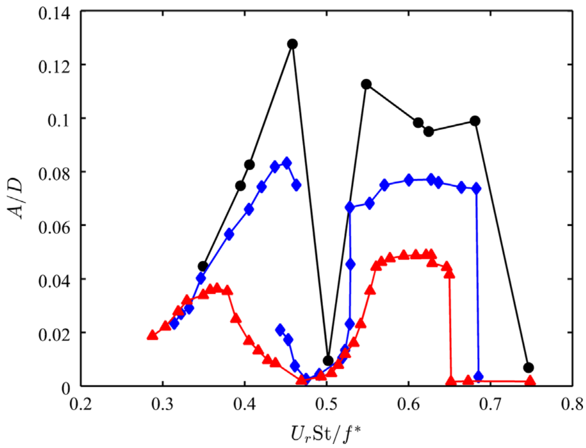

Fig. 1. Amplitude response of a cylinder undergoing streamwise VIV; Jauvtis and Williamson (2003) (pivoted cylinder, $m^* = 6.9$, $\zeta = 0.0014$, closed black circles); Aguirre (1977) ($m^* = 1.23$, $\zeta = 0.0018$, blue diamonds); Okajima et al. (2004) ($m^*\zeta = 0.195$, red triangles). These studies did not provide information on f^*, which is here assumed to remain equal to 1. The characteristic reduction in amplitude at $U_r\text{St} \approx 0.5$ is clear. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

However, when the cylinder is free to move in the streamwise direction, the synchronisation between the unsteady drag force and the cylinder vibration coincides with a sudden reduction in amplitude (Aguirre, 1977; Jauvtis and Williamson, 2003; Okajima et al., 2004). This paradoxical feature of VIV can be seen in Fig. 1, which shows the results of three previous studies; the reduction in vibration amplitude at resonance is in contrast to almost all other forms of fluid–structure interaction and remains poorly understood (Konstantinidis, 2014).

Nishihara et al. (2005) measured the fluid forces acting on a cylinder forced to oscillate in the streamwise direction at $A/D = 0.05$ for a range of reduced velocities and found that near $U_r\text{St}/f^* = 0.5$ the phase difference between the cylinder displacement and the drag force changed such that energy was transferred from the cylinder (i.e. it was a damping force), which they proposed to be the cause of the counter-intuitive reduction in amplitude in this region. A similar argument was presented by Konstantinidis et al. (2005) and Konstantinidis and Liang (2011), who examined the wake of a cylinder in pulsating flow and observed a change in the phase of the vortex-shedding near $U_r\text{St}/f^* = 0.5$. However, Morse and Williamson (2009) showed that the fluid force will *always* provide negative excitation (i.e. a damping force) if the cylinder is forced to oscillate at an amplitude above which it would oscillate in the free-vibration case. Konstantinidis and Liang (2011) also note this issue, pointing out that the forced oscillation experiments do not take into account the fact that the phase of the drag force with respect to the cylinder displacement will depend on the vibration amplitude. In light of this, the findings of Nishihara et al. (2005) could be said to be known a priori and the cause of the reduction in A/D near $U_r\text{St}/f^* = 0.5$ remains unclear.

In order to fully understand the complex coupling between the wake in the structural motion, knowledge of the fluid forces acting on the cylinder is required. However, it is often difficult in practice to accurately measure the forces acting on a freely oscillating body; for many experimental configurations it may not be possible to attach strain gauges to the body or its supports, and the measurements may be inaccurate when the amplitude of the forces is low (Noca et al., 1999). Khalak and Williamson (1999) showed that by manipulating the equations of motion of a single degree of freedom cylinder, the amplitude and phase of the fluid forces can be expressed in terms of the displacement and the structural properties of the cylinder. This approach also captures the dependence of the phase difference between the fluid forces and the cylinder motion on A/D, which is often neglected in forced oscillation experiments.

This brief communication presents estimates of the fluid forces acting on a cylinder free to move only in the streamwise direction, using a similar approach to that of Khalak and Williamson (1999), in order to provide insight into the fluid excitation in streamwise vortex-induced vibrations. In particular, we seek to address the question of what causes the paradoxical reduction in vibration amplitude at resonance.

2. Experimental details

2.1. Test facilities

The experiments were performed in a closed-loop water tunnel, which has been described in detail by Konstantinidis et al. (2003) and Cagney and Balabani (2013c). It contained a 72 mm × 72 mm test-section, which was made of Perspex, to allow optical access.

In order to support the cylinder within the flow such that it was free to move only by translation in the streamwise direction, it was suspended at either end using fishing wires. The wires were aligned normal to the cylinder axis and the