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Vortex-induced vibrations of a flexibly-mounted inclined cylinder

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ABSTRACT

The majority of studies on vortex-induced vibrations of a flexibly-mounted rigid cylinder are for the cases where the flow direction is perpendicular to the long axis of the structure. However, in many engineering applications, such as cable stays in bridges and mooring lines of floating offshore wind turbines, the flow direction may not be perpendicular to the structure. To understand the vortex shedding behind a fixed inclined cylinder, the Independence Principle (IP) has been used. The IP assumes that an inclined cylinder behaves similarly to a normal-incidence case, if only the component of the free stream velocity normal to the cylinder axis is considered. The IP neglects the effect of the axial component of the flow, which seems reasonable for small angles of inclination, but not for large angles. In the present study, a series of experiments have been conducted on a flexibly-mounted rigid cylinder placed inclined to the oncoming flow with various angles of inclination ($0^\circ < \theta < 75^\circ$) in a range of Reynolds numbers from 500 to 4000 to investigate how the angle of inclination affects VIV. A rigid cylinder was mounted on springs, and air bearings were used to reduce the structural damping of the system. The system was placed in the test-section of a recirculating water tunnel and the crossflow displacements were measured at each flow velocity. Even at high angles of inclination, large-amplitude oscillations were observed. As the angle of inclination was increased, the lock-in range (the range of reduced flow velocities for which the cylinder oscillates with a large amplitude) started at a higher reduced velocity. When only the normal component of the oncoming flow was considered, the onset of lock-in was observed to be at the same normalized flow velocity for all angles of inclination except for 75°. However, the width of the lock-in region, its pattern, the maximum amplitude of oscillations and its corresponding normalized reduced velocity were not following the results of a normal-incidence case entirely. Flow visualizations showed a vortex shedding parallel to the cylinder′s axis for all the angles of inclination considered. The influence of a slight change in the added mass as well as the direction of the inclined cylinder on the response was studied as well.

1. Introduction

Vortex-induced vibrations (VIV) of a rigid cylinder inclined to the oncoming flow is not studied as extensively as the case of a normal-incidence cylinder, despite its applications in the offshore risers, mooring lines of the floating offshore wind turbines and subsea pipelines, to name a few, where the flow direction may not always be perpendicular to the long axis of

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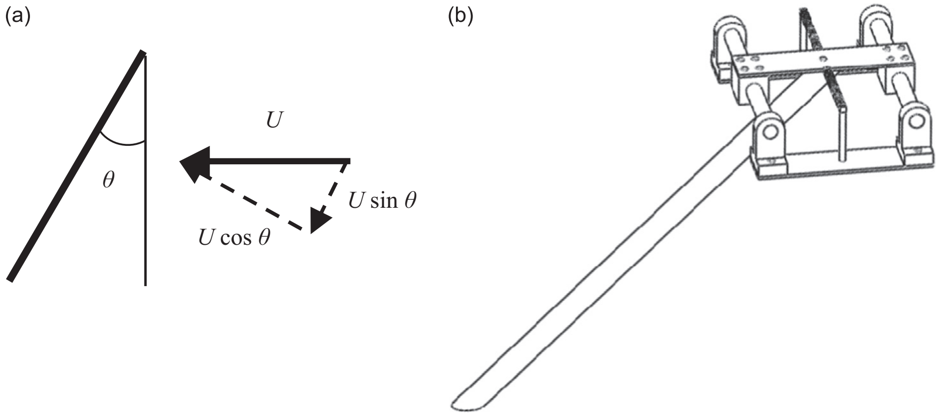

Fig. 1. (a) An inclined cylinder placed in flow along with the normal and axial components of flow velocity and (b) a schematic of the experimental set-up.

the structure. Extensive studies on VIV of flexibly-mounted rigid cylinders placed normal to the oncoming flow exist and many comprehensive review papers have been published (e.g., Bearman, 1984; Sarpkaya, 2004; Williamson and Govardhan, 2004; Vandiver, 2012). Vortex-induced vibrations of flexible cylinders placed normal to the flow have been studied extensively as well (e.g., Wu et al., 2012; Bourguet et al., 2011, 2012; Modarres-Sadeghi et al., 2010, 2011). In the case of cylinders inclined to the oncoming flow, an existing hypothesis – called the Independence Principle (IP) and mainly used for the fixed cylinders – states that the inclined cylinders can be treated as the normal-incidence ones, if only the component of the free stream velocity normal to the cylinder axis is considered. This approach neglects the effect of the axial component of the flow velocity, which is legit for small angles of inclination, but not when the angle of inclination increases. The angle of inclination is defined as the angle between the cylinder axis and the plane normal to the oncoming flow (θ in Fig. 1). When a cylinder is placed at an angle of inclination of θ, the axial component of the oncoming flow is $U \sin\theta$ and its normal component is $U \cos\theta$. Zero angle of inclination corresponds to a cylinder perpendicular to the oncoming flow. A cylinder inclined away from the oncoming flow is considered to have a positive angle of inclination and otherwise.

For a fixed inclined rigid cylinder, studies conducted by Surry and Surry (1967), Van Atta (1968), Ramberg (1983), Kozakiewicz et al. (1995), Thakur et al. (2004), Yeo and Jones (2008) and Zhao et al. (2009) among others suggest that the cylinder behaves similarly to a normal-incidence cylinder up to an inclination of around 40–50°. Lam et al. (2010, 2012) investigated the influence of waviness on the flow past a fixed yawed cylinder using large eddy simulation. In the case of a flexibly-mounted inclined cylinder, experimental (Hanson, 1966; Ramberg, 1983; Franzini et al., 2009) and numerical studies (Lucor and Karniadakis, 2003; Willden and Guerbi, 2010) have been conducted to study the IP based on the Strouhal number (St), drag coefficient (C_D) and the angle of vortex shedding.

Van Atta (1968) investigated angles of inclination within the range of $50^\circ \le \theta \le 75^\circ$ on hot wires. He confirmed that large oscillations could be seen for such high angles and that the maximum-amplitude region lies in the normalized reduced velocity ($U_n^* = U\cos\theta / f_N D$) range of 5.8–6.4. King (1977) justified taking the component of the flow velocity ($U\cos\theta$) to calculate the reduced velocity and drag forces by performing flow visualization tests. He demonstrated that flow over –34° in-line oscillating inclined cylinder was normal to the cylinder axis. The existence of the axial flow was also evident and it was different in the case of positively and negatively inclined cylinders. Positive angles of inclination lead the flow to move downward in the wake of the cylinder, and negative angles caused the flow to move upward. He also showed that the inclined cylinders response was identical for positive and negative angles of inclination ($-45^\circ < \theta < 45^\circ$). Ramberg (1983) studied the effect of the angle of inclination on circular cylinders forced to vibrate in a Reynolds number range of 160–460. He observed parallel vortex shedding till $\theta = 50^\circ$ and summarized that the end conditions dominate the flow around an inclined cylinder.

Lucor and Karniadakis (2003) performed direct numerical simulation (DNS) to validate the IP for stationery and freely vibrating rigid cylinders. They considered angles of inclinations of $\theta = -60^\circ$ and -70° in a cylinder with a mass-damping coefficient of $m^*\zeta = 0.006$ and an aspect ratio (L/D) of 22 at a constant Reynolds number: Re = 1000. They observed that for the larger inclination, the maximum amplitude response decreases ($A^* = 0.63$ for –60° and $A^* = 0.52$ for –70°). They also showed that for both angles of inclination, the maximum amplitude lies in the range of normalized reduced velocities, U_n^*, stated by King (1977) and Ramberg (1983). For a freely vibrating cylinder, the vortex shedding was parallel to the cylinder axis. In addition, they found that the drag forces were higher than predicted by the IP.

Franzini et al. (2009) performed experiments on inclined cylinders free to oscillate in the crossflow direction till $\theta = 45^\circ$ and observed that the lock-in occurs in the same normalized reduced velocity range as stated by King (1977) and Ramberg (1983). Finally, Willden and Guerbi (2010) performed forced oscillation tests across a range of oscillating frequencies (f/f_S) at a fixed amplitude of oscillation ($A/D = 0.3$), emphasizing on the variation of the component of the lift coefficient in phase with the cylinder's velocity C_{Lv}. For $\theta = 60^\circ$, they observed two excitation regimes: The first wider regime around $f/f_S = 0.75$ resulted in parallel vortex shedding, and the second small regime around $f/f_S = 1$ resulted in slantwise vortex shedding.