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Vortex-induced vibrations of a neutrally buoyant circular cylinder near a plane wall

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ABSTRACT

This paper presents an experimental study of the motions, drag force and vortex shedding patterns of an elastically mounted circular cylinder, which is held at various heights above a plane wall and is subject to vortex-induced vibration (VIV) in the transverse direction. The cylinder is neutrally buoyant with a mass ratio $m^*=1.0$ and has a low damping ratio $\zeta=0.0173$. Effects of the gap ratio (S/D) ranged from 0.05 to 2.5 and the free-stream velocity (U) ranged from 0.15 to 0.65 m/s (corresponding to $3000 \le \mathrm{Re} \le 13\ 000$, and $1.53 \le U^* \le 6.62$) are examined. The flow around the cylinder has been measured using particle image velocimetry (PIV), in conjunction with direct measurements of the dynamic drag force on the cylinder using a piezoelectric load cell. Results of the vibrating cylinder under unbounded (or free-standing) condition, as well as those of a near-wall stationary cylinder at the same gap ratios, are also provided. For the free-standing cylinder, the transition from the initial branch to the upper branch is characterized by a switch of vortex pattern from the classical 2S mode to the newly-discovered $2P_O$ mode by Morse and Williamson (2009). The nearby wall not only affects the amplitude and frequency of vibration, but also leads to non-linearities in the cylinder response as evidenced by the presence of super-harmonics in the drag force spectrum. In contrast to the case of a stationary cylinder that vortex shedding is suppressed below a critical gap ratio ($S/D \approx 0.3$), the elastically mounted cylinder always vibrates even at the smallest gap ratio $S/D=0.05$. Due to the proximity of the plane wall, the vortices shed from the vibrating cylinder that would otherwise be in a double-sided vortex street pattern (either 2S or $2P_O$ mode) under free-standing condition are arranged into a single-sided pattern.

1. Introduction

Vortex-induced vibration (VIV) of cylindrical structures is a challenge in many branches of engineering, for example marine pipelines, offshore risers, bridge piers, and so on. The practical significance of cylinder VIV has received much attention over the past several decades, see for example the reviews by Sarpkaya (2004), Williamson and Govardhan (2004, 2008) and Bearman (2011) regarding the progress, current state and debate, as well as some unresolved problems.

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Most previous studies are focused on the paradigm of a freely vibrating, elastically mounted rigid cylinder placed in uniform cross-flow under unbounded (or free-standing) condition. The principal dynamics giving rise to VIV of a cylinder, which could be a combination of transverse and in-line vibrations (or oscillations), are the spanwise von Kármán vortex pairs alternately shed from two sides of the cylinder. The resulting unsteady force on the cylinder can lead to ‘lock-in’ (or ‘synchronization’) phenomenon that is characterized by an amplification of cylinder's vibration amplitude, which can be up to the order of the cylinder diameter.

It has been shown that the VIV characteristics depend not only on the combined parameter—the mass–damping ratio ($m^*\zeta$, where the mass ratio m^* is defined as the ratio of cylinder mass to the displaced mass of fluid, and ζ is the ratio of damping coefficient to critical damping coefficient), but also on m^* and ζ individually. Khalak and Williamson (1999) found that the cylinder response, depending on the magnitude of $m^*\zeta$, may be of two different types. For low $m^*\zeta$, the response curve composes three distinct branches when plotted against the reduced velocity ($U^*=U/f_ND$, where U is the free-stream velocity, f_N is the natural structural frequency in still fluid and D is the cylinder diameter), namely: the ‘initial’, ‘upper’ and ‘lower’ branches. For high $m^*\zeta$, however, the upper branch does not exist at all. The classical definition of lock-in, namely the cylinder's vibration frequency (f_{osc}) is close to the natural frequency (f_N), or $f^*(=f_{osc}/f_N)\approx 1.0$, is valid only for heavy structures with $m^*=O(100)$, since most of the early experiments were conducted in air. On the other hand, most of recent research studies use water as the working medium (due to practical applications in marine engineering), resulting in much smaller mass ratios $m^*=O(10)$–$O(1)$. In this case, f^* may reach much higher values than unity. Therefore, Khalak and Williamson (1999) suggested that for light structures, the matching between the vortex shedding frequency (f_V) and the body's vibration frequency (f_{osc}) is a more suitable definition of lock-in.

The distinct branches in the response curve may be associated with different vortex shedding modes in the wake of the vibrating cylinder, for example the ‘2S’ mode (two single vortices per cycle, i.e., the familiar von Kármán vortex street), ‘2P’ mode (two pairs of vortices per cycle), and asymmetric ‘P+S’ mode (a pair of vortices and a single vortex per cycle), as originally proposed by Williamson and Roshko (1988). Recently, Morse and Williamson (2009) reported results of controlled vibration experiments of a cylinder with extremely fine resolution at two constant Reynolds numbers, Re=4000 and 12 000. Besides the P+S, 2S and 2P modes, a new mode responsible for peak amplitude vibration has been identified, which is defined as the “$2P_{OVERLAP}$” or “$2P_O$” mode because its regime in the normalized amplitude–wavelength (A^*–λ^*) plane overlaps with other regions. This mode comprises two pairs of vortices in each cycle (similar to 2P mode), but the second vortex of each pair is distinctly smaller than the first vortex.

The present study considers the case that the cylinder is placed near a plane boundary – a flow configuration widely used in engineering practice as schematically shown in Fig. 1 – for example a submarine pipeline near seabed and cable-laying. VIV has long been recognized as one of the main causes of structural fatigue damage for this type of application (Bearman and Zdravkovich, 1978), and may also induce dynamic coupling with soil scour beneath a pipeline (e.g., Chiew, 1990; Yang et al., 2008). As compared to the case of a free-standing cylinder, the flow around the cylinder in proximity to a plane wall becomes more complex, since it involves the development of three shear layers, i.e., the two separated from the upper and lower sides of the cylinder, as well as the wall boundary layer. According to the previous findings on a near-wall stationary (fixed) cylinder (e.g., Lei et al., 1999; Wang and Tan, 2008), the flow depends mainly on three parameters: the Reynolds number (Re=UD/ν, where ν is the kinematic viscosity of fluid), the boundary layer thickness δ , and the height of gap S between the cylinder and the wall. Previous studies, mostly conducted in the subcritical regime (Re=10^3–10^5), have shown that the gap height to cylinder diameter ratio (S/D, abbreviated hereafter as the gap ratio) is the predominant parameter. When the cylinder is sufficiently close to the wall, the lower shear layer is interfered with the wall boundary layer and thus its vorticity strength becomes weak. Therefore, the periodic vortex shedding would be suppressed below a critical gap ratio (about $S/D=0.3$ according to previous studies).

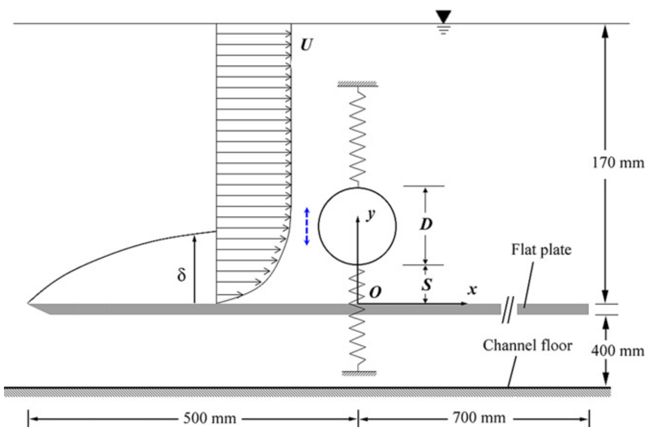

Fig. 1. Side view of the near-wall cylinder that is elastically mounted and subject to VIV in the transverse direction.