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Transverse vortex-induced vibration of spring-supported circular cylinder translating near a plane wall

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HIGHLIGHTS

- Peak vibration amplitude mildly increases with gap ratio.
- Vibration in the lock-in zone is controlled by either Strouhal or structural frequency.
- Phase lag of displacement behind lift for an isolated cylinder is predicted in theory.
- Both minimal gap and vibration amplitude determine vortex shedding pattern.
- Impact with wall causes no peculiar amplitude and frequency of cylinder vibration.

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ABSTRACT

Transverse vortex induced vibration of a spring-supported circular cylinder of low mass and zero damping translating near a plane wall at Re $= 100$ is numerically studied. We investigate three gap ratios. Results show that the size of lock-in zone increases and the peak vibration amplitude decreases with decreasing gap ratio. The peak vibration amplitude occurs at a larger reduced velocity for a smaller gap ratio. Wall proximity suppresses the beating phenomena of cylinder displacement and lift. The predominant vibration frequency is always equal to the vortex shedding frequency. The cylinder vibration in the lock-in zone is controlled by either the Strouhal frequency or the natural structure frequency in fluid, depending on the gap ratio and reduced velocity. The time-mean drag in the lock-in zone is always larger than that for an isolated non-vibrating (purely translating) cylinder. The time-mean lift is always positive. For an isolated cylinder, the phase lag of displacement behind lift is predicted in theory and is weakly correlated with the vortex shedding pattern. For a near-wall cylinder, both the minimal gap and vibration amplitude are important in determining the vortex shedding pattern. Impact with wall causes no peculiar amplitude and frequency of cylinder vibration.

1. Introduction

Uniform flow over a stationary circular cylinder has attracted much interest among researchers. Vortex shedding in the wake of the circular cylinder frequently occurs and causes periodic forcing to the cylinder. If the cylinder is allowed to vibrate freely in the flow, the vortex shedding and the cylinder motion will influence each other, eventually reaching a state of balanced vibration, called vortex induced vibration (VIV). The term "lock-in" denotes the occurrence of large vibration amplitude in VIV. The characteristics of the lock-in zone and the wake vortex structure would change significantly when the cylinder is close to a plane wall. Below the related literature is introduced under various topics, which are classified according to whether the plane wall exists or not.

VIV of an isolated circular cylinder.

VIV of an *isolated* circular cylinder, rigid or flexible, has been studied extensively in the literature. The parameters involved are the mass ratio $m^*(=m/m_d)$, damping ratio $\zeta(=c/c_{\mathrm{crit}})$, reduced velocity $U^*(=U/f_{nw}D)$, and $\mathrm{Re}(=UD/\nu)$ where $m=$ cylinder mass, $m_d=$ displaced fluid mass, $c=$ structural damping, $c_{\mathrm{crit}}=$ critical damping, $U=$ free-stream velocity, $f_{nw}=$ natural structure frequency in fluid, $D=$ cylinder diameter, and $\nu=$ kinematic viscosity. Some researchers defined the reduced velocity based on other velocity scales and/or structural natural frequency in vacuum. Related studies have been reviewed and discussed by Sarpkaya [1], Williamson and Govardhan [2], and Bearman [3].

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Particularly, there have been many publications on VIV of a spring-supported rigid cylinder at low mass-damping constrained to move transversely in a uniform free stream. Much progress has been made by Prof. Williamson's group with a series of physical experiments [4–6]. The main results can be summarized as follows. For a cylinder with low $m^*\zeta$, the response amplitude A versus the free-stream velocity U presents three distinct response branches; namely the *initial branch*, the *upper branch* and the *lower branch*. In the upper branch, the vibration amplitude can be twice as large as that for the classical high mass-damping case of Feng [7]. Meanwhile, the "lock-in" zone is dramatically extended in contrast to that of Feng [7]. Moreover, there is a correspondence of the 2S mode of vortex shedding (two single vortices shed per cycle) with the initial branch and the 2P mode of vortex shedding (two pair vortices shed per cycle) with the lower branch. The 2P mode was also observed in the upper branch, but the second vortex of each pair is much weaker than the first one. Some numerical studies have also reported the 2P mode [8,9]. Williamson and Govardhan [10] briefly summarized fundamental results and discoveries related to VIV with very low mass-damping.

In recent years, more and more researchers investigated VIV by computational fluid dynamics (CFD) techniques, e.g., Guilmineau and Queutey [11] and Wanderley et al. [12]. Al Jamal and Dalton [13] have reviewed some numerical studies on VIV of a circular cylinder.

VIV of a circular cylinder near a fixed plane wall in a free stream.

Two additional parameters have to be considered for this problem. The first is the gap ratio, G, defined as the distance between the cylinder bottom and the wall in the static equilibrium condition (i.e., when the spring force keeps zero with quiescent ambient fluid) normalized by D. The second is the wall boundary layer profile. In some works, the Reynolds number has been alternatively defined in terms of either the approach velocity at the cylinder center position or the time-mean velocity. For two-degree-of-freedom (2-dof) free span VIV [14], 2-dof rigid-cylinder VIV [15], and single-degree-of-freedom (1-dof) free span VIV [16], it was found that the presence of a plane boundary lowers the vibration amplitude. However, Yang et al. [17] reported that the vibration amplitude increases with decreasing gap ratio. Raghavan et al. [18] indicated that the vibration amplitude as function of gap ratio depends strongly on the Reynolds number and the wall boundary layer. Therefore, the correlation between the vibration amplitude and the gap ratio is still unclear due to insufficient exploration of these influential factors. On the other hand, the vibration frequency as a function of the reduced velocity also differs among various studies [19,18]. Yang et al. [17] indicated that both the onset reduced velocity and the width of the lock-in zone increase with decreasing gap ratio. Raghavan et al. [18] discovered that the onset of lock-in is gradual in near-wall cases while abrupt in isolated-cylinder cases and that the range of lock-in zone shifts to higher reduced velocities for smaller gap ratios.

Both Zhao and Cheng [20] and Wang et al. [21] reported significant rigid-cylinder VIVs even if the gap ratio is lowered down to 0.05, in contrast to the case of a stationary cylinder that vortex shedding is suppressed when $G \approx 0.3$. Due to the proximity of the plane wall, the vortices shed from the vibrating cylinder form a single-side vortex street.

Purely translating circular cylinder near a fixed plane wall.

Under this topic, experimental works include low-Re [22] and high-Re [23,24] studies; numerical works include low-Re [25–28] and high-Re [29] studies. In summary, the time-mean drag coefficient varies with the gap ratio in a way strongly depending on the Reynolds number and the gap ratio. When the cylinder is located in close proximity to the wall, the time-mean drag coefficient exhibits inconsistent variations with the gap ratio for some Reynolds number (10^5) between the works of Nishino et al. [24] and Bimbato et al. [29]. The time-mean lift coefficient increases with decreasing gap ratio for low Reynolds numbers ($100 \leq \mathrm{Re} \leq 600$) but varies in a complicated way with the gap ratio for a higher Reynolds number (10^5). In all the previous studies has been observed the gradual suppression of the Kármán-type vortex shedding as the gap ratio decreases. Some studies reported vortex shedding, at least single-side, even for small gap ratios, e.g., $G = 0.1$; some however observed a total cease of vortex shedding for $G \leq 0.3$. The difference would originate from different Reynolds numbers. We wonder whether these hydrodynamic characteristics persist if the cylinder is allowed to freely vibrate, as treated in the present study.

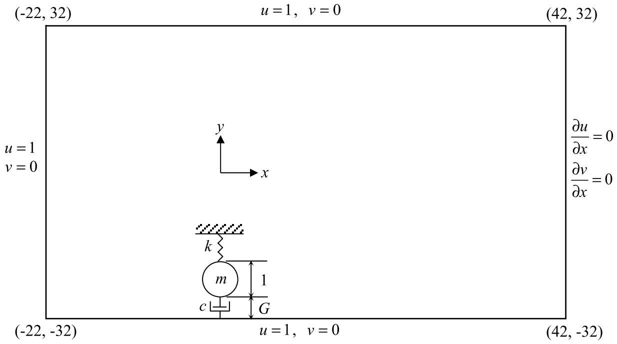

Fig. 1. Schematic diagram of the physical problem, computational domain, and boundary conditions. All quantities made dimensionless using the cylinder diameter D, incoming velocity (originally translating velocity of cylinder) U, and fluid density ρ_f as the characteristic length, velocity, and density respectively. The gap ratio, G, is defined as the distance between the cylinder bottom and the wall in the static equilibrium condition (i.e., when the spring force keeps zero with quiescent ambient fluid).

Present study—VIV of a translating circular cylinder near a fixed plane wall.

Focusing on low Reynolds numbers, we studied by computational fluid dynamics techniques the 1-dof VIV of a transversely spring-supported low-mass circular cylinder which is translating near a fixed plane wall. The structural damping was assumed zero to excite high-amplitude vibrations. To the author's knowledge, similar works have not been found in the literature. For numerical computations, the original scenario is replaced by an equivalent one where a uniform flow passes the cylinder and the wall moves, both with the translating velocity. All the quantities in this work are made dimensionless by taking the cylinder diameter D, incoming velocity (originally translating velocity) U, and fluid density ρ_f as the characteristic length, velocity, and density respectively. Fig. 1 depicts the configuration of the physical problem, computational domain, and boundary conditions. For 2-dof VIV of a circular cylinder near a fixed flat plate in a free stream, Tsahalis and Jones [14] and Jacobsen et al. [15] observed much larger (approximately 10 times) amplitudes in the transverse direction than in the in-line direction. The present assumption of 1-dof VIV in the transverse direction is thus justified though the wall is moving.

There are two major motives of the present study. Firstly, the problem configuration can serve as a preliminary model for objects moving near a ground. Examples include front/rear wings mounted on a racing car to create downforce, splitters and vortex generators attached on the car underside to increase downforce and/or reduce drag, actuator arm/slider/head above a spinning disk in a hard disk drive, wing structure of wing-in-ground (WIG) craft, etc. The present study can assist in understanding possible VIVs in these examples though the regime of Reynolds number, shape of object (circle), and dimensional complexity (two), of the present study are different from or simpler than those in the above examples. Secondly, for the scenario of uniform flow over a circular cylinder near a fixed wall with low Reynolds numbers, there are many applications including slurry flow past marine