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On the vortex-induced oscillations of a freely vibrating cylinder in the vicinity of a stationary plane wall

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ABSTRACT

A partitioned iterative scheme based on Petrov–Galerkin formulation by Jaiman et al. (2016) has been employed for simulating flow past a freely vibrating circular cylinder placed in proximity to a stationary plane wall. In the first part of this work, wall proximity effects on the vortex-induced vibrations (VIV) of an elastically mounted circular cylinder with two degree-of-freedom (2-DoF) are systematically studied in two-dimension (2D) laminar flow at Reynolds number, $Re = 200$ based on the diameter of cylinder. We investigate the hydrodynamic forces, vibration characteristics, phase relations, response frequencies, motion trajectories as well as vortex shedding patterns. For that purpose, a careful comparison has been established between the isolated and near-wall cylinders. Our 2D simulations reveal that (i) the vibrating near-wall cylinder exhibits larger streamwise oscillation and smaller streamwise vibration frequency as compared to its isolated counterpart owing to the energy transfer from fluid to cylinder and streamwise frequency lock-in caused by the suppression of shear layer roll-up from the bottom cylinder surface; (ii) the mechanism of this vortex shedding suppression for the near-wall configuration can be described by a cyclic process where counter-clockwise vortices shed from the bottom surface of the cylinder force the wall boundary layer to separate and induce secondary clockwise vortices which merge with clockwise vortices shed from the upper surface of the cylinder, eventually suppressing the counter-clockwise vortices from the bottom cylinder surface; (iii) beating oscillations during VIV are found at the critical reduced velocities entering and leaving the lock-in region; and (iv) VIV response becomes much more sensitive to the wall proximity in the energy-in phase than in the energy-out phase. In the second part, we perform three-dimensional (3D) simulations for VIV of a circular cylinder for both isolated and near-wall cases at subcritical $Re = 1000$. We compare the hydrodynamic forces and vibration characteristics in 3D with the results corresponding to the 2D study at $Re = 200$. We show that the wall proximity effects on VIV are also pronounced in 3D with the following observations: (i) the wall proximity increases the mean lift force to a lesser extent as compared to 2D at $Re = 200$; (ii) the wall proximity also enhances the streamwise oscillation to a lesser extent as compared to 2D at $Re = 200$; and (iii) the wall proximity increases the wavelength of streamwise vorticity blob.

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1. Introduction

The number of untapped onshore hydrocarbon reservoirs has continued to dwindle, leading to a growing need to develop offshore oil and gas technologies. Most of the shallow water hydrocarbons are transported via pipelines to onshore processing facilities. Despite the design and installation difficulties, the pipeline is still a cost effective choice in deep water. The uneven nature of seafloor or possible seabed scouring may cause free spanning along the pipeline. The span length can be easily 100 times that of the pipeline diameter, with a gap from the seabed which can range from essentially zero to more than 2–3 times the pipeline diameter, according to Sumer and Fredsøe (2006). When exposed to flows, free pipeline spans are subjected to dynamic motions induced by currents or waves, referred to as vortex-induced vibrations (VIV), which can cause fatigue related failure of the pipelines. Damage associated with the fatigue of a pipeline undergoing vibrations is known to be proportional to the product of $A^4 f$ where A is the vibration amplitude and f is the vibration frequency, as indicated in Tsahalis (1983). In the short term, small amplitude vibrations with high frequencies may not be detrimental. In the long run, however, they can naturally result in serious consequences due to fatigue. Therefore, the understanding of VIV of a free-span pipeline is of significant importance for offshore industry. The problem of a free-span along the pipeline can be modelled by the configuration in which flow is past an elastically mounted circular cylinder with two degree-of-freedom (2-DoF) in proximity to a stationary plane wall. The numerical studies of VIV of a circular cylinder near a fixed plane wall serve as a foundation to improve pipeline design and installation guidelines.

Most of the previous studies on VIV were generally focused on an isolated circular cylinder placed in a uniform cross-flow without wall proximity effects. There are a number of comprehensive review works on this topic in recent years, such as Williamson and Govardhan (2004, 2008), Sarpkaya (2004), and Bearman (2011). In Williamson and Govardhan (2004), a map of vortex shedding modes (2S, 2P and P+S) was presented. Sarpkaya (2004) summarised the intrinsic nature of VIV of circular cylindrical structures subjected to steady uniform flow. In Williamson and Govardhan (2008), the authors summarised some fundamental results on VIV with low mass and damping with new numerical and experimental techniques. The effects of Reynolds number, Re, on VIV responses of both isolated and tandem cylinders were reviewed in Bearman (2011), in which the Reynolds number based on cylinder diameter D is defined as $Re = U_\infty D/\nu$, where U_∞ denotes the freestream velocity and ν is the kinematic viscosity of the fluid.

Investigations at low Reynolds numbers include the experimental study conducted by Anagnostopoulos and Bearman (1992) in laminar flow at Re from 90 to 150. Direct numerical simulations carried out in low Re regime include Shiels et al. (2001), Guilmineau and Queutey (2002), Leontini et al. (2006), and Prasanth and Mittal (2009). In the work by Shiels et al. (2001), the dimensionless peak transverse oscillation amplitude is 0.59 for a massless cylinder with 1-DoF motion, achieving a good agreement with experimental results (Anagnostopoulos and Bearman, 1992). The vortex sheddings of a forced streamwisely oscillating cylinder in water at rest with $Re=100$ and $KC = U_\infty T/D = 5$ (where T denotes the period of oscillation) and a forced transversely oscillating cylinder in a uniform flow at $Re=185$ were numerically investigated in Guilmineau and Queutey (2002). In Leontini et al. (2006), the authors performed 2D simulations at $Re=200$ and found that the genesis of the higher-Re flow behaviour is also present in low-Re 2D flow in terms of regimes of cylinder response, frequency and phase response of the cylinder. The authors (Prasanth and Mittal, 2009) numerically studied VIV of two circular cylinders in both tandem and staggered arrangements using a stabilized finite element method in 2D at $Re=100$.

The authors (Khalak and Williamson, 1999) found that the cylinder response can be characterised by two types of VIV behaviour. With a low mass damping, there are three distinct branches in the response curve with the variation of reduced velocity. The three branches are termed as the initial, upper and lower branches. With high mass damping, the upper branch does not exist. The distinct branches in the response curve are associated with different vortex shedding modes at the wake region of the cylinder. Govardhan and Williamson (2000) found that for 1-DoF vibrating cylinder with high mass damping, two branches of the response are found, namely the initial and lower branches. The vortex wake on the initial branch comprises a 2S mode while a 2P mode is shown on the lower branch. Jeon and Gharib (2001) found that in 2-DoF VIV the streamwise displacement inhibits the formation of the 2P vortex shedding mode.

The proximity of a plane wall introduces complications to the vortex shedding in the wake. One of the earliest experiments studying ground effect on a circular cylinder was reported by Taneda's experiment (Taneda, 1998), where the flow behind a circular cylinder towed through stagnant water close to a fixed ground was visualised at $Re=170$. The water and ground moved together relative to the cylinder and thus there was essentially no boundary layer formed on the ground. Regular alternate vortex shedding occurred at a gap ratio, e/D where e denotes the gap distance, of 0.6, while only a weak single row of vortices was shed at $e/D = 0.1$.

When the wall in proximity is stationary, a boundary layer forms along the wall. The development of three shear layers is involved, namely the two separated from the upper and lower sides of the cylinder, as well as the wall boundary layer. Bearman and Zdravkovich (1978) showed that the vortex shedding is suppressed if e/D is small enough. Studies by Zdravkovich (1985) and Lin et al. (2005), carried out at $Re=3550$ and 780, respectively, showed the cessation of regular vortex shedding for a stationary cylinder near a fixed plane wall. Other studies of stationary cylinder near a fixed wall by Lei et al. (2000) and Wang and Tan (2008) showed that Re, e/D and boundary layer thickness, δ/D, are parameters affecting the flow for a cylinder near a fixed wall. Ong et al. (2008) applied the standard high Reynolds number k–ω model at $Re = 1.0 \times 10^4$–4.8×10^4 with $\delta/D = 0.14$–2, finding that under-predictions of the essential hydrodynamic quantities were observed in the subcritical flow regime due to the limited capacity of the k–ε model in capturing the vortex shedding correctly. Ong et al. (2010) carried out numerical studies on stationary near-wall cylinder in the turbulent regime. For the