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Flow-induced vibration of two side-by-side square cylinders with combined translational motions

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ABSTRACT

This paper presents a series of two-dimensional numerical simulations of flow-induced vibrations (FIV) and coupled wake flow behind two identical square cylinders in a side-by-side configuration at Re=200. The computational results of stationary configuration are firstly investigated and compared with the existing experimental observations as a function of gap ratio g^*, which is the ratio of spacing between the inner cylinder surfaces to the diameter of the cylinder. Consistent with the experimental measurements, four distinct regimes have been observed namely: (i) the single bluff-body, (ii) the gap flow with narrow and wide streets, (iii) the coupled-vortex street regime, and (iv) the quasi-independent vortex shedding. We estimate the merging downstream distance of two vortex streets and compare it against the measurement trend for the gap ratio range $0.4 \lesssim g^* \lesssim 2.0$. We next investigate the configuration of two elastically mounted square cylinders, which are free to oscillate in both streamwise and transverse directions. Instead of independent vibrations due to the individual fluid forces, the two square cylinders are tied together as a single rigid body with a fixed relative position between them. The role of flow passing through the gap between two cylinders is examined by exploring interactions of shear layers with the gap flow in the near-wake region. Through controlled numerical experiments, we show that the gap flow mechanism has a profound role on both vortex-induced vibration and galloping regimes corresponding to low and high reduced velocities, respectively. The fluid–structure simulations are performed via a nonlinear partitioned iterative scheme for the variational coupled system based on the Navier–Stokes equations and rigid body dynamics. For the freely vibrating condition, all the 2D simulations are computed at Reynolds number Re = 200, mass ratio m^* = 10, damping ratio $\zeta = 0$ and reduced velocity $U_r \in [1, 50]$ and the four regimes are considered based on the stationary analysis. The effects of reduced velocity on the force variation, the vibration amplitudes and the vorticity contours are analyzed systematically to understand the underlying FIV physics of side-by-side cylinders in the four regimes. For a fixed mass-damping parameter, we introduce simple correlations for the prediction of amplitudes for the vortex-induced vibration and galloping modes of freely vibrating side-by-side cylinders in the four regimes.

1. Introduction

Offshore and civil engineering structures interacting with surrounding flow are inevitably subject to unsteady fluid forces and they may undergo flow-induced vibrations (FIV) at certain conditions (Blevins, 1990; Paidoussis et al., 2011). In addition to wide

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range of engineering applications, flow-induced vibrations are important from a fundamental standpoint due to their richness with respect to underlying nonlinear physics and vorticity dynamics. The flow past flexibly mounted cylinders provides a generic FIV model setup and has been extensively studied both numerically and experimentally for understanding coupled nonlinear dynamics of flow-structure interaction. Of particular interest of this work is to investigate square-shaped cylinder, which is widely used as a fundamental structural member in engineering structures, in particular in offshore floating bodies such as semi-submersible and tension leg platforms. Predicting nonlinear physics of free vibrations in such square-shaped structures is a challenging task due to complex wake interference, vortex-induced vibrations, galloping and several other self-excited instabilities. These coupled instabilities associated with rhythmic oscillations are undesirable for the riser and mooring fatigue (Det Norske Veritas, 2010). The flow interference and shielding effects of tandem and side-by-side configurations significantly alter the wake dynamics and net hydrodynamic forces on an offshore floating structure. In the field of offshore engineering, there is a growing need for fundamental understanding and optimization of the hydrodynamic loads and flow-induced motions of multicolumn floating structures.

It is well known that bluff body structures immersed in a flow stream undergo vortex-induced vibration (VIV) over a range of reduced velocity for both circular and square sections (Williamson and Roshko, 1988; Carmo et al., 2011; Bearman, 2011; Bearman et al., 1987; Luo and Bearman, 1990). As a function of reduced velocity U_r, in comparison with vibrating circular cylinder, square-shaped structure immersed in a flow stream undergoes the combination of both vortex resonance and galloping (Bearman et al., 1987; Bearman, 1984; Parkinson and Corless, 1988; Luo, 1992; Luo et al., 2003b, 2007; Jaiman et al., 2015). An experimental study on the FIV of a single square cylinder in water flow at a low mass ratio (cylinder mass to displaced fluid mass) of 2.4 for two different incidence angles was carried by Zhao et al. (2010), whereby both VIV and galloping phenomena were observed. When the natural frequency coincides with the vortex shedding frequency, the immersed structure experiences *lock-in* phenomenon, as shown in numerous VIV studies for single circular cylinder (Williamson and Roshko, 1988; Khalak and Williamson, 1997, 1999; Govardhan and Williamson, 2000). Furthermore, two-degrees-of-freedom (2-DOF) vibrating circular cylinder has been extensively investigated through forced and free vibrations in Gharib and Jeon (2001), Luo et al. (2003a), Williamson and Govardhan (2004), Lucora and Triantafyllou (2008) and Bearman (2009). In recent numerical investigations (Zhao et al., 2013; Jaiman et al., 2016a, b) for a freely vibrating square cylinder, beating phenomenon was observed in the time history of displacements at U_r=5 where the maximum vibration amplitude occurs at the peak of *lock-in* region. In Joly et al. (2012) and Roura et al. (2009), galloping of single square cylinder was numerically studied at low Reynolds numbers and found that galloping would happen for the Reynolds number larger than 140 and the amplitude decreased abruptly for decreasing values of the mass ratio close to 3. In Sen et al. (2015), the effect of mass ratio on vibrating square cylinder has been studied at low Reynolds number and the authors in Jaiman et al. (2015) investigated the role of rounding on the free vibration of square cylinders. The rounded cylinders underwent vortex-induced vibration alone in the synchronization regime, whereas the motion of the basic square was vortex-induced vibration at lower U_r and showed galloping at higher side of U_r in the laminar flow regime. The flow has been found to be periodic for vortex-induced motion and quasi-periodic for galloping. For a vibrating square cylinder, the components of response were the lower branch, desynchronization and galloping. Removal of the sharp corners of square cylinder remarkably modified the flow dynamics and vibration characteristics. The lower branch and desynchronization mainly characterized the response dynamics of rounded cylinders at low Reynolds number (Jaiman et al., 2015).

Apart from the investigations of single square cylinder, there have been some experimental and numerical studies on multi-cylinder structures, especially on the tandem arrangement of two cylinders mounted elastically. For the safety and reliability of offshore structures, the understanding of FIV dynamics of multi-cylinder configuration is important for the development of suppression or mitigation methods and devices. Multi-cylinder system is also common in various civil, mechanical and nuclear engineering applications, and understanding the coupled dynamical effects are paramount to avoid potential system failures. There are numerous experimental (Zdravkovich, 1985; Assi et al., 2006; Meneghini et al., 2010; Bearman and Huera-Huartea, 2011) and numerical investigations (Papaioannou et al., 2007; Carmo et al., 2011; Mysa et al., 2016) on the physics of free vibrations of elastically mounted circular cylinders in tandem arrangement. In contrast, the studies on the side-by-side configuration are not as many as that of tandem configuration of two circular cylinders and it is less understood especially when flip-flop is involved in a side-by-side arrangement. During the flip-flop of the gap flow between the two cylinders, the jet-like fluid injection could not maintain its straight path and has a tendency to deflect intermittently with new asymmetric states. This spontaneous broken symmetry is associated to complex nonlinear dynamical interactions. Kolar et al. (1997) studied the characteristics of turbulent wake flow over two side-by-side identical square cylinders ($g^* = 2$) at Reynolds number around Re=23,100 through two-component laser-Doppler velocimetry system. A symmetric wake flow about the central line has been observed. The Strouhal number was higher than the single square cylinder counterpart. However, the work was done with high blockage effects, which resulted strong blockage effects on the vortex dynamics. Yen and Liu (2011) conducted experiments in an open-loop wind tunnel by using a smoke-wire scheme to capture the flow patterns, and measured the surface pressure and vortex-shedding frequency by using a pressure transducer and a hot-wire anemometer for the Reynolds number $2,262 < Re < 28,000$ and the gap ratio $0.6 \le g^* \le 12$. The flow dynamics was classified into three regimes, namely single bluff-body, gap-flow and coupled vortex-shedding modes. The maximum values of drag coefficient and Strouhal number were found in the single-mode regime, while the minimum drag coefficient and Strouhal number have been observed in the gap-flow mode. The authors in Alam et al. (2011) and Alam and Zhou (2013) conducted a comprehensive experimental campaign to characterize the wake dynamics of two side-by-side square cylinders at Reynolds number about 47,000 and for the gap ratio $0 \le g^* \le 5.0$. Instead of the three regimes reported in Yen and Liu (2011), the authors (Alam and Zhou, 2013) identified four flow regimes, where the gap flow mode has been further divided into two regimes. In the range $g^* = 0.3 - 1.2$ for the gap flow regime, the jet develops to a certain adequate strength and separates the wake into a narrow and a broad vortex streets with high and low vortex-shedding frequencies, respectively. This can be referred to as the two-frequency regime. The range