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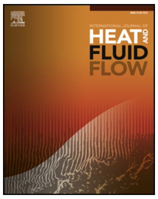

Fluid-structure interaction of combined and independent configurations of two side-by-side square cylinders at low Reynolds number

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ABSTRACT

The objective of this paper is to investigate the vibrational characteristics and the coupled wake dynamics of two elastically mounted side-by-side square cylinders in a uniform flow stream. A series of fluid-structure interaction simulations is performed at low Reynolds number for two vibrating configurations, namely combined and independent. In the combined vibrating configuration, two square cylinders are tied together through a linkage as one single rigid body with a fixed relative position between them. The elastically mounted system is free to vibrate with the two-degrees-of-freedom (2-DOF) in the streamwise and transverse directions. For the independent vibrating condition, each cylinder is free to vibrate independently with 2-DOF motion in the streamwise and transverse directions which result into the coupled 4-DOF system interacting with the vortex wakes. The computational results of the independent vibrating condition are compared with the combined vibrating counterpart for identical fluid-structure parameters. Three representative gap ratios 1.6 and 2 are selected for a detailed comparison, whereby the gap ratio g^* is defined as the spacing between the inner cylinder surfaces to the diameter of the cylinder. Two-dimensional simulations are examined for a broad range of reduced velocity $U_r \in [1, 40]$ at mass ratio $m^* = 10$. The effects of reduced velocity on the force responses, the vibration amplitudes, and the vorticity contours are analyzed systematically to understand the underlying vortex-induced vibration (VIV) and the wake physics of the side-by-side system. The effect of three-dimensional flow mechanics is further explored and the independent vibrating condition at the reduced velocity corresponding to the maximum synchronization is considered for two representative gap ratios $g^* = 1.2$ and 2. All the simulations are performed via a nonlinear partitioned iterative scheme for the coupled fluid-structure system based on the Navier–Stokes and the rigid-body equations.

1. Introduction

Squared cross-section structures are commonly used as a fundamental member in a wide range of offshore, aerospace and civil engineering applications. When the structure is free to vibrate, there exists a strong fluid-structure coupling between the motion of structure and the wake dynamics (Parkinson, 1989; Bearman, 2009; Williamson and Roshko, 1988; Khalak and Williamson, 1996; Govardhan and Williamson, 2000; Williamson and Jauvtis, 2004; Jauvtis and Williamson, 2004). For a squared cross-section structure immersed in the flow stream, the vibrational response usually exhibits a combination of both vortex synchronization and galloping as functions of Reynolds number, reduced velocity, mass-damping and various geometry related parameters (Bearman et al., 1987; Luo and Bearman, 1990; Luo, 1992; Luo et al., 2003; 2007; Sen et al., 2010; Joly et al., 2011; Zhao et al., 2013; Jaiman et al., 2015). The side-by-side configuration of multiple squared structures has many implications in offshore engineering applications, e.g., a large scale floating production, storage, and offloading (FPSO) and a semi-submersible platform operating in a side-by-side arrangement with wind and ocean current flows, multiple cylinders bolted together with a common pontoon base in a floating platform, tender assisted drilling along with a tension leg platform. Apart from their engineering relevance, the fluid-structure interaction of multiple square-shaped cylinders offers the canonical side-by-side configuration to explore the fundamental behavior of wakes behind such vibrating structures. The accurate prediction of flow-induced vibration (FIV) in a multi-cylinder configuration is a formidable task for researchers due to the complex wake interference, vortex-induced vibrations, galloping, and several other self-excited instabilities for both the side-by-side and tandem configurations of square cylinders. The large oscillations due to fluid-structure interaction can be dangerous and can result in the structural failure, for example in offshore platforms at high ocean

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currents Veritas (2010). The coupled fluid-structure responses of multiple square cylinder systems are significantly different and are much more complex than the isolated square cylinder due to the effects of vortex-to-vortex and the interactions between the cylinder and the gap flow. The recent FIV investigations on tandem and side-by-side square cylinders by Guan et al. (2015); Jaiman et al. (2016b); Guan et al. (2016) were carried out at low Reynolds numbers $Re\left(=\frac{\rho^f UD}{\mu^f}\right) \in [100, 200]$ for mass ratio $m^* \in [2.6, 10]$, where ρ^f is the fluid density, μ^f denotes the dynamic viscosity, U and D denote the free-stream speed and the diameter of cylinder, respectively. The present study considers the Reynolds number $Re = 200$ and the mass ratio $m^* = 10$ for the comparison of combined and independent configurations for side-by-side square cylinders. Although the configurations considered herein may seem a somewhat simplification of realistic engineering situations, they contain the important features of gap flow dynamics and the characteristics of flow-induced vibration.

Previous experimental and numerical investigations for two side-by-side cylinder configuration have been mainly conducted in the stationary condition. In particular, several experimental works of multiple circular cylinders have been done in past decades for a side-by-side configuration Zdravkovich (1977, 1987); Sumner (2010). For the two identical side-by-side square cylinders at a fixed gap ratio ($g^* = 2$), Kolar et al. (1997) studied the wake flow through a two-component laser-Doppler velocimetry system at Reynolds number of $Re = 23,000$. Compared with the isolated square cylinder, the two-cylinder system was found to have a higher Strouhal number $St = f_{vs}D/U$; e.g., the single cylinder with $St{=}0.13$ and the two-cylinder with $St{=}0.14$, where f_{vs} denotes the vortex shedding frequency. Yen and Liu (2011) conducted experiments in an open-loop wind tunnel by means of a smoke-wire scheme to capture the flow profiles, and measured the surface pressure and the vortex shedding frequency through a pressure transducer and a hot-wire anemometer for the Reynolds number $2262 < Re < 28,000$ and the gap ratio $0.6 \leq g^* \leq 12$. The flow characteristics were classified into three regimes as a function of gap ratio, namely the single bluff-body, the gap-flow and the coupled vortex-shedding. From the classical experimental measurements of Biermann and Herrnstein (1933) for circular cylinders, the maximum value of drag coefficient was found for the single-bluff-body regime ($g^* < 1$) and the minimum at bistable/flip-flop regime ($g^* > 1$) with respect to the single isolated cylinder at $Re = 4.7 \times 10^4$. The flip-flop regime is defined as the bistable regime where the gap flow between the cylinders are biased, resulting in one wide and one narrow vortex street (Bearman and Wadcock, 1973). In the event of flip-flop, the jet-like gap flow fails to maintain its original straight path and has a tendency to deflect intermittently with new asymmetric states. This intermittent bistable instability causes highly chaotic and irregular variations in the flow dynamic variables. The cylinder with the deflected gap flow has a narrower near-wake region than its counterpart with the wider vortex street, as discussed in Kim and Alam (2015); Liu and Jaiman (2016). In the recent experiments, Alam et al. (2011) and Alam and Zhou (2013) characterized the wake dynamics of two side-by-side square cylinders at Reynolds number about 47,000 and for the gap ratio $0 \leq g^* \leq 5.0$. Instead of the three regimes reported by Yen and Liu (2011); Alam and Zhou (2013) identified four flow regimes, where the gap flow mode has been further decomposed into two regimes. In the range of $g^* = 0.3 - 1.2$ for the gap flow, the jet develops a certain adequate strength and separates the wake into one narrow and one broad vortex streets with high and low vortex shedding frequencies, respectively. The range $g^* = 1.2 - 2.0$ can be considered as the transition regime, where the three distinct vortex frequencies are observed intermittently as compared to the two-frequency mode.

Most of the works of both circular and square cylinders are concentrated on the stationary condition for a broad range of Reynolds numbers. For the vibrating condition, a few works can be traced in the literature and almost all of those studies are concentrated on circular cylinders. The numerical investigation of two elastically mounted coupled circular cylinders with one-degree-of-freedom (1-DOF) in the side-by-side arrangement was carried out by Cui et al. (2014). The distance between two cylinders was kept at $g^* = 2$ and the RANS equations are solved by the 2D finite element method at $Re = 5000$ and $m^* = 2$. From their numerical studies, the authors observed five different response regimes, namely the first-mode lock-in regime, the second-mode lock-in regime, the sum-frequency lock-in regime and two transition regimes, with symmetric and asymmetric flow profiles. Kim and Alam (2015) conducted the experiments to examine FIV characteristics of two identical circular cylinders in a side-by-side arrangement for gap ratio $g^* = 0.1 - 3.2$ to cover all possible flow regimes and observed four characteristic vibrational patterns as a function of the gap ratio. While Regime I ($0.1 \leq g^* < 0.2$) is characterized as a single-bluff-body whereby both cylinders vibrate with maximum amplitudes at similar reduced velocity (twice that for an isolated cylinder), no vibration is observed for Regime II ($0.2 \leq g^* \leq 0.9$), as the gap flow between the cylinders act as base-bleed, delaying the vortex formation in the wake region. For Regime III ($0.9 < g^* < 2.1$), the maximum amplitude of vibration of one cylinder occurs at a smaller U_r and other at a higher U_r, associated with narrow wake and wide wake profiles, respectively. In Regime IV, the vibrations of each cylinder resemble the response of the isolated cylinder counterpart. Another recent numerical work for two side-by-side freely vibrating circular cylinders was carried out by Chen et al. (2015) using an immersed boundary method for three low Reynolds numbers ($Re = 80$, 100 and 125) at $m^* = 2$ and $g^* = 1.5$. Six flow regimes were observed based on the vortex in-phase or anti-phase interactions and the regions of asymmetric vibration and symmetry hysteresis as functions of VIV parameters U_r and Re were discussed.

A comprehensive numerical study of the side-by-side circular cylinder arrangement in a two-dimensional laminar flow environment was conducted by Liu and Jaiman (2016), in which one of the cylinders is elastically mounted and only vibrates in the transverse direction, while its counterpart remains stationary in a uniform flow stream. Several fundamental questions related to the coupling between VIV and the gap flow were investigated. In particular, the frequency synchronization process in the flip-flop regime was studied systematically. Recently, Zhao et al. (2016) performed two-dimensional (2D) numerical studies for two circular cylinders in the side-by-side and tandem arrangements for a gap ratio in the range $0.5 < g^* < 3$, for mass ratio $m^* = 2.5$ and reduced velocity $U_r \in [1, 30]$. From the numerical experiments, the authors observed a maximum response amplitude at $g^* = 0.5$ in the vibrating Regime I and strong vortex interactions were observed at $g^* = 1$ with the out-of-phase vortex shedding mode. In another recent study of Griffith et al. (2017), the gap flow dynamics and flow-induced vibrations of two staggered circular cylinders were investigated at $Re = 200$ for a range of cross-stream offset at fixed streamwise separation of $L/D = 1.5$. Specifically, the gap flow dynamics of the staggered vibrating cylinder arrangement has some relevance to the present study. Using the variational partitioned iterative fluid-structure formulation, Guan and Jaiman (2017) simulated the combined vibrating condition, whereby the two cylinders are bonded into one single rigid body and the joint system undergoes 2-DOF motion in a uniform flow. Analogous to the circular cylinder configuration, four regimes were considered based on the stationary counterpart analysis at $Re{=}200$. The flow regimes are namely the single rectangular body; Regime I ($g^* \leq 0.4$), the gap flow; Regime II ($0.4 \leq g^* \leq 1.2$), the coupled flow; Regime III ($1.2 \leq g^* \leq 2.5$) and the quasi-independent flow; Regime IV ($\geq$ 2.5). The range of gap ratio for each regime in the vibrating condition was altered that of the stationary counterpart. The critical vortex merging distance is predicted via numerical simulations for the first time. The sensitivity of gap flow regime has been investigated and a chaotic-like behavior has been reported, in which no vortex synchronization occurs in the transition regime and the vibration amplitudes increase linearly with the reduced velocity. A saturation of