Ocean Engineering 110 (2015) 244–257

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Flow-induced vibrations of two side-by-side circular cylinders: Asymmetric vibration, symmetry hysteresis and near-wake patterns

Weilin Chen[a], Chunning Ji[a,b,*], Rui Wang[c], Dong Xu[a], Jordan Campbell[d]

[a] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China
[b] State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu 610065, China
[c] Department of Naval Architecture and Marine Engineering, University of Michigan, Ann Arbor, MI 48109-2145, USA
[d] School of Civil Engineering, University of Queensland, Brisbane, QLD 4072, Australia

ARTICLE INFO

Article history:
Received 23 June 2015
Accepted 17 October 2015
Available online 3 November 2015

Keywords:
Flow-induced vibration
Two side-by-side circular cylinders
Asymmetric vibration
Symmetry hysteresis
Immersed boundary method

ABSTRACT

The immersed boundary method was utilised to numerically investigate the flow-induced vibrations (FIV) of two elastically mounted side-by-side circular cylinders in a uniform flow with low Reynolds numbers. Six distinct near-wake patterns were observed; the irregular (IR) pattern, the in-phase synchronized (IS) pattern, the anti-phase synchronized (AS) pattern, the biased anti-phase synchronized (BAS) pattern, the out-of-phase flip-flopping (OFF) pattern, and the hybrid (HB) pattern. A detailed analysis on the asymmetric vibration and symmetry hysteresis phenomena was conducted by focusing on the near-wake patterns and the interaction between the cylinders. Results show that the asymmetric vibrations of the cylinders are closely related with the stably biased gap flow and the resulting narrow-wide near-wake pattern. While the symmetry hysteresis is caused by the coexistence of two distinct near-wake patterns – the IS and the BAS patterns. The transition processes of BAS to IS and IS to BAS were illustrated by using the long-time histories of the lift coefficients, the combined lift coefficient and the phase differences of lift and displacement. Results on hydrodynamic forces and the vibration responses show that the HB pattern is a combination of IS, OFF and AS patterns with a very long period.

1. Introduction

The configuration of two side-by-side circular cylinders in a cross-flow is found in many engineering problems. Three distinct near-wake patterns were observed at different normalized spacing ratios s/D, where s is the center-to-center distance of two cylinders and D is the cylinders' diameter (Zdravkovich, 1977; Sumner, 2010). For flow around two side-by-side cylinders with a small spacing ratio ($s/D < 1.1-1.2$), no vortex sheds from the gap between the cylinders. The vortices alternatively shed from the free-stream side of the cylinders and thus form a single vortex street in the wake (Sumner et al., 1999; Alam and Zhou, 2007). When the spacing ratio is large ($s/D > 2.0-2.5$), vortices shed from both the gap and free-stream sides. Consequently, two parallel vortex streets, which have a similar shape and identical vortex-shedding frequencies, can be observed in the wake. The near-wake pattern is either in-phase or anti-phase synchronized, but the latter is dominant (Bearman and Wadcock, 1973; Williamson, 1985; Le Gal et al., 1990; Sumner et al., 1999; Meneghini et al., 2001; Zhou et al., 2002; Alam et al., 2003). For the case with an intermediate spacing ratio ($1.1-1.2 < s/D < 2.0-2.2$), the near-wake behind the cylinders is asymmetric and the gap flow biases towards one of the cylinders, resulting in a narrow-wide wake pattern (Bearman and Wadcock, 1973; Williamson, 1985; Kim and Durbin, 1988; Sumner et al., 1999; Zhou et al., 2002; Alam et al., 2003).

Bearman and Wadcock (1973) found in their experimental study that the biased gap flow was not stable and changed its direction from one side to the other occasionally. Kim and Durbin (1988) named the phenomenon as flip-flopping (FF) and further found that the flip-over time interval of the gap flow was several orders of magnitude longer than the period of vortex shedding. In the FF, the cylinder with a wide near-wake has a low vortex-shedding frequency and drag force, compared to the other cylinder with a narrow near-wake. This is due to the shear layers being closer to the rear end of cylinder when they roll up (Roshko, 1954).

In low-Re laminar flows, the switching time of FF is only a few vortex shedding periods (Kang, 2003; Carini et al., 2014b). In a numerical study, Kang (2003) found that with $Re = 40-160$ the switching of biased gap flow direction was not as sharp as that in

* Corresponding author at: State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China.
E-mail address: cnji@tju.edu.cn (C. Ji).

http://dx.doi.org/10.1016/j.oceaneng.2015.10.028
0029-8018/

high-Re flows and the near-wake was no longer periodic. Carini et al. (2014b) found that the wake instability in the FF stemmed from the in-phase vortex shedding in the gap flow, instead of originating from the interaction between two bi-stable asymmetric wake patterns. Carini et al. (2015b) numerically investigated flow around two side-by-side circular cylinders with $\mathrm{Re}=50-90$ and established that the FF originated from a Neimark–Sacker bifurcation of the in-phase vortex shedding cycle, which was significantly different to the high Re flip-flopping.

For free or forced vibrations of two side-by-side circular cylinders in laminar and turbulent flows, the near-wake pattern becomes more complicated due to the interaction of vibrating cylinders and the flow around them. Xu et al. (2008) studied forced vibration of two side-by-side circular cylinders at $s/D=1.2-3.2$ and $\mathrm{Re}=200$. Results showed that the cylinders' oscillation had significant influence on the near-wake patterns. The vortex shedding locked on the cylinders' oscillation only if the cylinders' amplitudes were larger than a threshold. Bao et al. (2013) investigated the forced in-phase vibrations of two side-by-side cylinders at $s/D=1.2-4.0$ and $\mathrm{Re}=100$. Five flow response regimes, including three non-locked regimes (quasi-periodic mode I, II and periodic doubling) and two lock-on regimes ('pure' and 'imperfect' type of lock-on response) were observed. The five flow response regimes were identified by analyzing the different characteristics shown in the power spectra of lift force, the phase portraits of lift force against cylinder motion, the time histories of energy transfer and flow fields visualized in vorticity contours. Zhao (2013) numerically studied the flow-induced vibrations of two rigidly coupled circular cylinders at $\mathrm{Re}=150$ and $s/D=1.5-6.0$ and found that the vibration response of two cylinders was a combination of vortex-induced vibration (VIV) and galloping at $s/D=1.5$ and 2.0. In addition, the response of two side-by-side circular cylinders at $s/D=4.0$ and 6.0 is very similar to that of an isolated circular cylinder. Lakshmana and Deshkulkarni (1988) experimentally investigated the flow-induced vibration of two side-by-side circular cylinders at $\mathrm{Re}=4500$ and found that the interaction between the cylinders could be neglected when the spacing ratio was larger than 5.0. Cui et al. (2014) studied the vibration of two side-by-side circular cylinders at $\mathrm{Re}=3000$ and $s/D=3.0$. Results indicated that the interference between two cylinders was fairly weak when the vibration amplitude was small but became stronger with the increasing vibration amplitude. The authors (Chen et al., 2015) numerically investigated the flow-induced vibrations of two side-by-side circular cylinders at $s/D=2.0-5.0$ and $\mathrm{Re}=100$. It was shown that when the spacing ratio is larger than 4.0, the interaction between two cylinders is negligible and the vibration response is similar to that of the VIV of an isolated circular cylinder. Six distinct near-wake patterns were found in the parametric plane of U_r (the reduced velocity) and s/D, i.e., the irregular pattern (IR), the in-phase flip-flopping pattern (IFF), the out-of-phase flip-flopping pattern (OFF), the in-phase synchronized pattern (IS), the anti-phase synchronized pattern (AS), and the biased anti-phase synchronized pattern (BAS), respectively. The BAS pattern is distinguished by a stably biased gap flow and a narrow-wide wake pattern and was only found at the beginning of lock-in region of the case with a moderate spacing ratio of $s/D=2.5$. This is quite an interesting phenomenon firstly observed in a previous study by the same authors. It was noted that, despite the boundary conditions of numerical simulation being symmetric, the near-wake and the vibration response of cylinders are consistently asymmetric. However, due to the relative large U_r increment adopted in Chen et al. (2015), the precise boundary of the BAS region was not well-defined. This paper further investigates the BAS near-wake pattern, together with two new phenomena; the asymmetric vibration and symmetry hysteresis of the responses of two side-by-side cylinders, by using much smaller increments in U_r. Because the asymmetric vibration and symmetry hysteresis only exist within a small range of the spacing ratio, $s/D=2.5$ was adopted in the present paper. Although a number of studies have been done on the FIV of two side-by-side cylinders, there exists, to the author's best knowledge, no investigation on these new phenomena.

The mechanisms of FIV of two side-by-side cylinders are valuable for engineering application. At the moment, the unsatisfying accuracy of widely used wake-oscillator models is due to the fact that the dynamics of vortices in near-wake is not well-understood, especially for the FIV of two side-by-side cylinders in which complicated interactions between two near-wakes are involved. One of the benefits of low-Re VIV/FIV simulations is that they provide indispensable results, complementary to the results with high-Re, for improving the wake-oscillator models. Thus, many papers on low-Re VIV/FIV of cylinders have recently been published on Ocean Engineering, such as Wanderley and Soares (2015), Han et al. (2015) and Sung et al. (2015). The present study focuses on the asymmetric vibration and the symmetry hysteresis – two new phenomena which are far from being well-understood, and thus are helpful for improving the comprehension on the complicated wake dynamics.

The rest of this paper is organized as follows. The numerical methods are introduced in Section 2. In Section 3, a validation case – flow around two side-by-side stationary circular cylinders is presented. Section 4 shows the vibration responses of two side-by-side circular cylinders oscillating in the cross-flow direction, together with the hydrodynamic forces on the cylinders and the near-wake patterns. In addition, the features of the asymmetric vibration and symmetry hysteresis, together with the underlying mechanisms are discussed. The conclusions are given in Section 5.

2. Methodology

The governing equations for fluid flow are the incompressible Navier–Stokes equations. The two-step predictor-corrector procedure was adopted for the decoupling of the flow governing equations. The resultant pressure Poisson equation was solved by using the BiCGSTAB scheme and the multi-grid method. The second-order Adams–Bashforth time marching scheme was employed to calculate a new velocity field.

The dynamics of two side-by-side elastically supported circular cylinders was simplified as a mass-damper-spring system. The governing equations for cylinder motion are based on Newton's Second Law and was simply solved by using the standard Newmark-β method with a second-order temporal accuracy. In this study, the cylinders are free to oscillate in the cross-flow direction and the structural damping was set to zero for the purpose of exciting large vibration amplitudes of the cylinders.

The fluid-structure interaction (FSI) is simulated by using the immersed boundary (IB) method which was first introduced by Peskin (1972) in the simulation of blood flow around the flexible leaflet of a human heart. In the framework of the IB method, the flow governing equations are discretized on a fixed Cartesian grid, which generally does not conform to the geometry of moving solids. As a result, the boundary conditions on the fluid–cylinder interface (which manifest the interaction between fluid and structure) cannot be imposed directly. Instead, an extra body force is added into the momentum equation to take such interaction into account. Compared with conventional FSI numerical methods, the IB method has significant advantages, particularly in the FSI simulations with topological changes.

For the sake of conciseness, details of the methodology are not presented here and readers are referred to previous work (Ji et al., 2012; Chen et al., 2015) for further information.