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Response and wake patterns of two side-by-side elastically supported circular cylinders in uniform laminar cross-flow

Weilin Chen [a], Chunning Ji [a,*], Wanhai Xu [a], Shuang Liu [a], Jordan Campbell [b]

[a] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China
[b] School of Civil Engineering, University of Queensland, Brisbane, QLD 4072, Australia

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ABSTRACT

Vortex-induced vibrations (VIV) of two side-by-side elastically supported circular cylinders in a uniform flow with the Reynolds number of 100 are numerically investigated by using the immersed boundary method. The cylinders are constrained to oscillate in the cross-flow direction with a center-to-center spacing ratio T/D ranging from 2 to 5. The structural damping is set to zero to enable large vibration amplitudes in the range of reduced velocity $U_r = 3-10$. It is found that the proximity of the cylinders does not have a significant impact to the lock-in region and cylinder responses, except at a small spacing ratio of $T/D = 2$. The critical spacing ratio is determined as $T/D = 4$ and beyond that the interaction between the cylinders is negligible. The following six near-wake patterns are observed; the irregular pattern, in-phase flip-flopping pattern, out-of-phase flip-flopping pattern, in-phase-synchronized pattern, antiphase-synchronized pattern and the biased antiphase-synchronized pattern. These patterns are plotted in a plane of U_r and T/D, together with approximate borderlines to distinguish one region from the others. The time histories, spectral features and wavelet transform contours of drag and lift forces are presented to elucidate the mechanisms of the in-phase and out-of-phase flip-flopping phenomena. It is established that the in-phase flip-flopping stems from the long-short near-wake pattern and its low-frequency flip-over, whereas the out-of-phase pattern originates from the large vortex shedding from the fictitious bluff-body with an augmented characteristic length.

1. Introduction

The circular cylinder is a fundamental shape of many engineering structures such as; heat-exchanger tubes, marine risers and transmission lines. These structures, in flowing air or water, are subjected to vortex-induced vibration (VIV) and have the risk of structural failure. In this paper, the VIV of two side-by-side elastically supported circular cylinders in a uniform cross-flow with the Reynolds number of $\mathrm{Re} = 100$ is numerically investigated on the purpose of shedding new light for the responses and wake patterns of the VIV of two side-by-side cylinders.

For flow past two side-by-side stationary circular cylinders, six near-wake patterns were found at various spacing ratios T/D and Reynolds numbers Re, where T is the center-to-center distance between the cylinders and D is their diameter. For a small spacing ratio ($T/D < 1.1-1.2$), the cylinders are too close to each other and no vortex sheds from the gap side of both

* Corresponding author.
E-mail address: cnji@tju.edu.cn (C. Ji).

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cylinders. As a consequence, the vortices shed from the free-stream side pair and form a single vortex street behind the cylinders. This is called the single bluff-body pattern. For side-by-side circular cylinders with a larger spacing ratio of $1.1-1.2<T/D<2.0-2.2$, the biased gap flow pattern (also called the flip-flopping pattern) appears in the near-wake featured by a gap flow bias towards one of the cylinders and a wide-narrow wake pattern (Afgan et al., 2011). The bias direction switches spontaneously and intermittently from one side to the other and the time scale has a close relationship with the Reynolds number (Kim and Durbin, 1988). When the spacing ratio is $T/D>2.0-2.5$, two parallel vortex streets are observed behind the cylinders. The two vortex streets have the same vortex-shedding frequency, and they might be in-phase (in-phase-synchronized pattern) or in anti-phase (antiphase-synchronized pattern). However, the anti-phase pattern appears to be dominant (Bearman and Wadcock, 1973; Williamson, 1985; Peschard and Gal, 1996; Sumner et al., 1999; Meneghini et al., 2001; Zhou et al., 2002). Williamson (1985) found in his experiments that vortices shed in-phase coalesce together and evolve into a larger binary-vortex street in the far-wake, which is significantly different from the case with a stable anti-phase vortex-shedding. The steady pattern occurs when the Reynolds number is low enough that no vortex sheds from the cylinders, the flow is steady and symmetric relative to the centerline. The deflected pattern occurs by changing the Reynolds number as well as the spacing ratio. The gap flow is invariantly deflected to one side which makes the wake pattern differentiate from the flip-flopping pattern. Readers are referred to the reviews of Zdravkovich (1977), Zdravkovich (2003) and Sumner (2010) for details.

For flow around two side-by-side stationary cylinders, the biased gap flow pattern is always one of the focused objectives. Through wind tunnel experiments, Bearman and Wadcock (1973) found that the gap flow direction switches from one side to the other intermittently because of the wake interaction between two cylinders. Kim and Durbin (1988) defined this phenomenon as flip-flopping (referred to as FF hereafter) and found the switching of two asymmetric states happen randomly. The time scale for FF is always a few orders of magnitude larger than that of the vortex-shedding and increases with decreasing Reynolds number (Williamson, 1985) before the flow goes into the laminar regime. In the FF state, the vortex-shedding frequency and the drag on the cylinder with a wide wake are smaller, compared with those on the other one with a narrow wake. This occurs because the roll-up of shear layers in the narrow near-wake is closer to the cylinders' rear end, and thus results in a larger drag force (Roshko, 1954). Williamson (1985) reported a two-frequency mode of the lift and regarded the high frequency component as a result of the existence of harmonic vortex-shedding patterns. However, Zhou et al. (2001) took it as the interactions between the gap vortex pair and the vortex shed from the free-stream side of the cylinder with the narrow near-wake. Wang and Zhou (2005) experimentally studied the vortex interactions of flow around two side-by-side cylinders with different spacing ratios in the Reynolds number range of $\mathrm{Re}=120-1100$. They found that when the gap vortex in the wide near-wake slightly leads the gap vortex in the narrow near-wake, the two opposite-signed vortices shed from the cylinder with the narrow wake usually engaged in pairing, which yields a relatively low-pressure region between them and thus attracting the gap vortex in the wide near-wake. This kind of interaction may have played the role of stabilizing the gap flow direction. However, when the gap vortex in the wide near-wake lags, the gap vortex in the wide near-wake does not merge with the vortices in the narrow near-wake, and this kind of interaction may prompt the gap flow direction changing from one side to the other (refer to Fig. 8 in Wang and Zhou, 2005). Alam et al. (2003) applied the wavelet analysis to study the switching of the FF phenomenon of two side-by-side cylinders with $\mathrm{Re}=5.5\times10^4$ and $T/D=1.1-6.0$. It was established that the lift switches among low, intermediate and high-frequency modes and the ratios between the frequencies are not integral numbers. This differed from many previous conclusions that the high frequency values three times of the low frequency (Bearman and Wadcock, 1973; Williamson, 1985; Mahir and Rockwell, 1996; Sumner et al., 1999; Zhou et al., 2001).

For FF in high-Re turbulent flows, the scale of the switching time is a few orders of magnitude longer than the vortex-shedding period (Bearman and Wadcock, 1973; Kim and Durbin, 1988; Zhou et al., 2002). While the switching time is only several times of the vortex-shedding period in low-Re laminar flows (Kang, 2003; Harichandan and Roy, 2010; Carini et al., 2014). The gap flow direction and drag coefficient do not change so abruptly as in turbulent flows (Kang, 2003). All evidence indicates that the low-Re FF is distinct from the high-Re FF.

Because of the obvious advantages (e.g., abundant information and ignorable interference) of numerical simulations of laminar flow, investigations on FF with a low Reynolds number are mainly carried out numerically. For example, Kang (2003) studied flow characteristics behind two side-by-side cylinders at $\mathrm{Re}=40-160$ with $T/D<6$ and found that the FF wake patterns are no longer periodic. Harichandan and Roy (2010) numerically studied the flow around two side-by-side cylinders and an unrepeatability was observed in the lift and drag coefficients. Mizushima and Ino (2008) applied linear stability analyses and found that various kinds of wake patterns arise from the linear instability of the steady symmetric flow, and further proved that the steady deflected flow originates from the instability of the basic flow and only occurs in a very small parameter region of T/D and Re.

Although the origin of the high-Re and low-Re FFs is not yet fully understood, what can be assured is that the gap flow plays a crucial role in the formation of the flip-flopping phenomena. Brun et al. (2004) experimentally investigated the roles of the shear layer instability in the generation of FF and found two flow regimes in the near-wake. When the Reynolds number is smaller than a critical value $\mathrm{Re}_c\in[1000,1700]$, the gap flow is stably deflected to one side and the near-wake is asymmetric. However, when the Reynolds number is larger than the critical value, a random FF occurs and the third harmonic of vortex-shedding frequency appears in the wake oscillation. This is related to the development of Kelvin–Helmholtz vortices in the separated shear layers of the cylinders. They stated that the generation of FF is attributed to the birth of these Kelvin–Helmholtz instabilities and their intermittent nature. Although FF at low-Re is also related with the