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An experimental study on the hydrodynamic features of two side-by-side flexible cylinders undergoing flow-induced vibrations in a uniform flow

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ABSTRACT

Flow-induced vibrations (FIVs) of a group of flexible cylinders is a major concern in many engineering fields. The dynamic characteristics and hydrodynamic features of multiple flexible cylinders are significantly different from those of an isolated cylinder due to the influence of adjacent cylinders. A system of two side-by-side cylinders is one of the simplest cases of multiple cylinders. Currently, the hydrodynamic characteristics of two side-by-side flexible cylinders undergoing FIVs are unknown and require further investigation. In this paper, the hydrodynamic force coefficients for two side-by-side flexible cylinders with four spacing ratios (S/D = 3.0, 4.0, 6.0 and 8.0) were studied via an inverse analysis method based on the time-varying displacements obtained from experimental tests. The cross-flow (CF) or in-line (IL) fluctuating force coefficients of two cylinders are enlarged at the first- and second-order mode resonances in the CF direction for all four spacing ratios and the CF or IL fluctuating force frequencies of the two cylinders are slightly different from each other when $S/D \le 6.0$. Moreover, significant differences in lift coefficient of the two cylinders and the isolated cylinder are observed for S/D up to 6.0, and differences in varying drag coefficient exist for S/D up to 8.0. In the case of $S/D \le 6.0$, the CF or IL added mass coefficients of the two cylinders show large deviations. The disparity between the IL added mass coefficients still exists as S/D increases to 8.0. These results indicate that the wake interference between the two cylinders is still strong when $S/D \le 6.0$ in terms of the hydrodynamic forces. In addition, the wake interaction can considerably affect the hydrodynamic force in the IL direction, even when S/D is as large as 8.0.

1. Introduction

Flow-induced vibrations (FIVs) occur when wake vortices generate fluctuating forces on an elastically mounted rigid cylinder or a flexible cylinder in the cross-flow (CF) direction and the in-line (IL) direction. FIV is well known as a complex fluid-structure interaction (FSI) problem, and a large number of publications have focused on the behaviours of shedding vortices, FSI mechanisms, structural dynamic characteristics and hydrodynamic features [1–4]. Hydrodynamic force coefficients, which play a significant role in predicting FIVs in the engineering field, are worthy of comprehensive study [5,6]. The CF fluctuating force on an oscillatory cylinder can be decomposed into two parts. One part is in phase with the structural velocity and is referred to as lift; the other is in phase with the structural acceleration and is referred to as the CF added mass force [7]. Similarly, the IL fluctuating force can be

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decomposed into the varying drag and IL added mass force [8]. Some research work has been devoted to the hydrodynamic characteristics of an isolated cylinder undergoing vortex shedding [9–14].

Multi-cylinder systems are utilized in various mechanical, civil, ocean and nuclear engineering applications, such as transmission lines, heat exchangers, chimney stacks, marine risers, and mooring cables. The in-depth investigation of the hydrodynamic features of multi-cylinder system subjected to FIV is valuable for judging the fatigue damage and the safety life. Two cylinders in a side-by-side arrangement can be considered as one of the basic cells of multiple cylinders. Knowledge regarding the flow around two fixed cylinders is helpful for understanding the hydrodynamic characteristics of FIVs. Experimental and numerical studies of the flow around two fixed cylinders in a side-by-side arrangement have been conducted by many researchers [15–22]. Some research work has indicated that the flow regime behind two side-by-side cylinders can be classified into three categories depending on the spacing ratio, S/D (where S is the centre-to-centre separation distance and D is the cylinder diameter). Clearly, different flow regimes always exhibit different hydrodynamic features. At a small spacing ratio ($S/D < 1.1$–1.2), the two cylinders behave as a single bluff body, and a single vortex street forms in the wake. The mean drag of the cylinder pair was less than twice the drag of an isolated cylinder due to the gap flow [23]. At an intermediate spacing ratio (1.1–$1.2 \le S/D < 2.2$–2.7), a bistable biased gap flow emerges, namely, a narrow wake behind one cylinder with higher mean drag and lower mean lift, and a wide wake behind the other cylinder with lower mean drag and higher mean lift. Moreover, the fluctuating drag and lift are higher for a cylinder with a narrow wake [17]. At a large spacing ratio ($S/D \ge 2.2$–2.7), two coupled vortex streets occur, and the vortices of two cylinders shed in either an in-phase or anti-phase fashion. The values of the mean and fluctuating drag or lift of the two cylinders are almost identical [24]. When the spacing ratio is greater than 4.0–5.0, the interaction between the two wakes disappears, and the hydrodynamic forces of the cylinders are the same as those of an isolated cylinder [25].

The hydrodynamic features of two oscillatory cylinders are more complicated than those of an isolated one due to the interaction between adjacent cylinders. Several investigators have explored the FIV hydrodynamic behaviours of two elastically mounted cylinders or two forced-vibration cylinders in a side-by-side arrangement. Kim and Alam [24] conducted a free-vibration experiment to investigate the FIV features of two side-by-side cylinders with $S/D = 1.1$–4.2 and found that the wake flow of the two fixed cylinders and of the two oscillating cylinders are not the same. Notably, if a cylinder vibrated in the coupled vortex streets regime, symmetric wakes might transmute into narrow and wide wakes. Cui et al. [26] numerically investigated the FIVs of two elastically coupled cylinders in a side-by-side arrangement with $S/D = 3.0$. In the symmetric case, the root-mean-square (RMS) values of the CF fluctuating force coefficients were identical, except for several individual reduced velocities. However, the RMS values of the CF fluctuating force coefficients of one cylinder were significantly different from those of the other in the case of an asymmetric configuration. Chen et al. [27] numerically examined the FIVs of two side-by-side cylinders that could freely vibrate in the CF direction, with spacing ratio S/D ranging from 2.0 to 5.0. The narrow-wide near-wake pattern appearing for the two fixed cylinders was observed to be replaced by a long-short pattern for $S/D = 2.75$. The CF fluctuating force coefficient for the cylinder with a shorter near-wake had a larger amplitude and higher frequency than those of the other cylinder with a longer near-wake. In addition, Chen et al. [28] studied the asymmetric vibration, symmetry hysteresis and near-wake patterns of two side-by-side cylinders by analysing the hydrodynamic force coefficients. Zhao [29] numerically studied the FIVs of two rigidly coupled cylinders in a side-by-side arrangement with S/D values ranging from 1.5 to 6.0. The cylinders were allowed to oscillate only in the CF direction and have identical displacement. The max RMS values of the CF fluctuating force coefficients of the two cylinders differed for $S/D = 2.0$ and 4.0, and they were significantly greater than that of an isolated cylinder in the resonance region for $S/D = 4.0$ and 6.0. Bao et al. [30] investigated the CF FIVs of two side-by-side arranged cylinders that oscillated in in-phase mode and had spacing ratios ranging from 1.2 to 4.0. The numerical results indicated that the time-averaged CF fluctuating force coefficient was mainly affected by the spacing ratios, and the two cylinders acted in repelling form. For $S/D = 2.5$ and 4.0, the RMS values of the CF fluctuating force coefficients of the two cylinders were similar to those of a single oscillating cylinder within the lock-in regime.

The system of two rigid cylinders arranged side-by-side is a simplified model of some multi-cylinder systems appearing in various engineering applications. However, several structures have a high aspect ratio. These kinds of structures usually cannot be regarded as rigid ones. Zhou et al. [31] experimentally studied the free vibration of two fixed flexible cylinders in a side-by-side arrangement and indicated that structural flexibility, which has been ignored in many investigations, plays an important role in FIV. In addition, the flow around flexible cylinders was strongly correlated in the spanwise direction, which further complicates the FIV mechanism of two side-by-side flexible cylinders. Huera-Huarte and Gharib [32] investigated experimentally the response and frequency characteristics of two side-by-side flexible cylinders undergoing FIVs. The two cylinders showed no synchronized motion for $S/D \ge 3.5$. However, the hydrodynamic features of the two flexible cylinders in this arrangement were not studied. Sanaati and Kato [33] carried out a series of model tests on two side-by-side flexible cylinders with $S/D = 2.75$ and 5.5. Strongly synchronized motion of the two cylinders was observed even when the spacing ratio was increased to 5.5, which conflicted with the result of Huera-Huarte and Gharib [32]. The total CF and IL fluctuating force coefficients of the two cylinders might have higher values than that of an isolated cylinder. For $S/D = 2.75$, the CF and IL fluctuating force coefficients of the cylinders were clearly different. The difference between the hydrodynamic force coefficients of the two cylinders was not obvious when $S/D = 5.5$, but they did not absolutely vanish.

More recently, Xu et al. [34] experimentally investigated the FIVs of two side-by-side flexible cylinders with four different spacing ratios ($S/D = 3.0$, 4.0, 6.0 and 8.0) in a towing tank. The proximity interference was observed to exist in the CF direction when $S/D \le 6$, and a strong interaction between the cylinders was observed in the IL direction even when the spacing ratio was 8.0. However, the FIV hydrodynamic features of the two side-by-side flexible cylinders are still unknown; hence, relevant research must be conducted immediately. Obviously, the hydrodynamic force distribution of an oscillating flexible cylinder is difficult to measure directly. However, several researchers have obtained the hydrodynamic force on a flexible cylinder via some inverse analysis methods [35–38]. The main aims of this paper are to study the FIV hydrodynamic characteristics of two side-by-side flexible cylinders in a