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Wake-induced vibrations of an elastically mounted cylinder located downstream of a stationary larger cylinder at low Reynolds numbers

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ABSTRACT

Two-dimensional numerical simulations of flow past two unequal-sized circular cylinders in tandem arrangement are performed at low Reynolds numbers (Re). The upstream larger cylinder is stationary, while the downstream cylinder has both one (transverse-only) and two (transverse and in-line) degrees of freedom (1-dof and 2-dof, respectively). The Re, based on the free stream velocity U_∞ and the downstream cylinder diameter d, varies between 50 and 200 with a wide range of reduced velocities U_r. The diameter of the upstream cylinder is twice that of the downstream cylinder, and the center-to-center spacing is 5.5d. In general, for the 1-dof case, the calculations show that the wake-induced vibrations (WIV) of the downstream cylinder are greatly amplified when compared to the case of a single cylinder or two equal-sized cylinders. The transverse amplitudes build up to a significantly higher level within and beyond the lock-in region, and the U_r associated with the peak amplitude shifts toward a higher value. The dominant wake pattern is 2S mode for Re=50 and 100, while with the increase of Re to 150 and 200, the P+S mode can be clearly observed at some lower U_r. For the 2-dof vibrations, the transverse response characteristics are similar to those presented in the corresponding 1-dof case. The in-line responses are generally much smaller, except for several significant vibrations resulting from in-line resonance. The obvious in-line vibration may induce a C (chaotic) vortex shedding mode for higher Re (Re=200). With regard to the 2-dof motion trajectories, besides the typical figure-eight pattern, several odd patterns such as figure-double eight and single-looped trajectories are also obtained due to the wake interference effect.
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1. Introduction

Vortex-induced vibration (VIV) of cylindrical structures is a subject that has attracted a lot of attentions due to its importance in engineering applications and in fluid dynamics research. Extensive studies have been mainly focused on 1-dof VIV of an elastically mounted circular cylinder in the transverse flow direction. It is well known that the lock-in or synchronization phenomenon occurs when the vibration frequency approaches the structural natural frequency. Different

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vortex shedding patterns, such as 2S mode (two single vortices are shed per cycle), 2P mode (two pairs of vortices are released per cycle) and P+S mode (a single vortex and a pair of vortices are released per cycle) can be observed depending on some important parameters such as the Reynolds number, the reduced velocity and the cylinder mass. The 2-dof VIV of a circular cylinder has also been studied. An interesting feature is that the motion orbit usually presents a figure-eight pattern because the frequency of the drag force is approximately twice that of the lift force. More details about the VIV of a single circular cylinder can be found in review papers by Williamson and Govardhan (2004), Sarpkaya (2004), Gabbai and Benaroya (2005), and Bearman (2011).

Multiple cylinders are more often encountered in practical engineering. When an elastically mounted cylinder is immersed in the wake of another bluff body, the wake-induced vibration (WIV) of the downstream cylinder is usually completely different from the VIV of a single cylinder in free stream. Many previous investigations, experimentally and numerically, have been focused on the WIV response involving two equal-sized circular cylinders (Assi et al., 2006, 2010; Bao et al., 2011; Bokaian and Geoola, 1984; Brika and Laneville, 1999; Carmo et al., 2007, 2011; Hover and Triantafyllou, 2001; King and Johns, 1976; Zdravkovich, 1985). As confirmed in these studies, the wake interference was able to lead to a wider lock-in range, and within this range the transverse vibration amplitudes of the downstream cylinder were larger than those of a single cylinder. Some experimental observations at high Re have also shown that the cylinders subjected to wake interference could experience galloping response (Assi et al., 2010; Bokaian and Geoola, 1984; Brika and Laneville, 1999; Hover and Triantafyllou, 2001). In addition, using two- and three-dimensional (2D and 3D) numerical simulations, Carmo et al. (2011) studied the WIV of two equal-sized cylinders in tandem arrangement at $\mathrm{Re}=150$ and 300. The upstream cylinder was fixed and the downstream cylinder was free to vibrate only transverse to the flow. Their results showed that the downstream cylinder sustained high-amplitude vibrations for higher reduced velocities outside the lock-in range, but not wake-induced galloping. The question would be: is there an upper limit of reduced velocity at which these vibrations cease? Carmo et al. (2013) conducted a further numerical study at infinite reduced velocity for $100 \le \mathrm{Re} \le 645$. They confirmed that there was not a delimited range of reduced velocity, within which the vibration occurred with significant amplitude.

In contrast, up to now there only exist a few studies on the WIV involving two unequal-sized cylinders. Lam and To (2003) experimentally investigated the transverse vibration of a flexibly mounted cylinder placed downstream of a larger cylinder at $720 \le \mathrm{Re} \le 3600$. The interfering larger cylinder had a diameter twice that of the vibrating cylinder. The authors observed that for spacing up to 2.34 times the larger cylinder diameter in the tandem arrangement, the flexible cylinder still exhibited negligible vibrations at nearly all reduced velocities, due to the shielding of the larger cylinder. Later on, To and Lam (2007) carried out an experimental study for the flexibly mounted cylinder placed upstream of the larger cylinder. They reported that galloping-type vibrations occurred when the flexible cylinder was placed just in front of the larger cylinder. Recently, Gao et al. (2014) experimentally studied the transverse vibration of a smaller cylinder in the wake of a larger cylinder for tandem arrangement at $\mathrm{Re}=7200$. The diameter ratio between two cylinders was 0.75. Their results revealed that the vibration amplitude of the smaller cylinder was lower than that of a single cylinder under the same flow condition, even though the spacing between two cylinders became sufficiently large. However, little information about the lock-in response was given because the reduced velocity in their computations was fixed at a value of 7.

At the present state of the art, the studies on the WIV characteristics of two unequal-sized cylinders, such as the lock-in responses, the flow patterns and the motion trajectories, are still lacking. The main purpose of this paper is to fill the knowledge gap on both 1-dof and 2-dof WIV of an elastically mounted cylinder behind a stationary larger cylinder and supplement the findings reported by others, using 2D numerical simulation. The diameter of the upstream cylinder is twice that of the vibrating cylinder. The two cylinders are arranged in tandem with a center-to-center spacing of $5.5d$. This spacing is expected to be sufficient to form strong wake interference between two cylinders. The Reynolds number is limited in the range of $50 \le \mathrm{Re} \le 200$, which has been widely considered in previous numerical studies. For each fixed Re, the reduced velocity ranges from 3.0 to 30.0 by changing the structural natural frequency. In this work, we try to answer the following questions: (i) Could the lock-in phenomenon occur? (ii) Could the downstream cylinder exhibit large-amplitude transverse vibration associated with the lock-in? (iii) How different would be the WIV responses of two unequal-sized cylinders, compared to those for the case of a single cylinder or two equal-sized cylinders? (iv) What kinds of flow patterns would appear? (v) Whether the in-line freedom has any effects on the transverse response? (vi) Which kinds of trajectories would the downstream cylinder with 2-dof move along?

The outline of this paper is organized as follows. Section 2 describes the mathematical and numerical background, including the numerical techniques to solve the fluid flow, the cylinder motion, the mesh motion and the fluid–solid interaction (FSI). Section 3 presents the physical description of the studied problem as well as the validation of the used computational code. The results and discussions are given in Section 4 and Section 5. Section 6 attempts to draw conclusions for this study and to deliver the answers to the above-mentioned questions.

2. Mathematic and numerical background

2.1. Equations for the incompressible fluid flow

The governing equations for fluid flow are the two-dimensional incompressible Navier–Stokes equations. The arbitrary Lagrangian–Eulerian (ALE) scheme (Donea et al., 1982) is applied to deal with the flow problem with moving boundaries.

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