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Vortex-induced vibration of two elastically coupled cylinders in side-by-side arrangement

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ABSTRACT

Vortex-induced vibration (VIV) of two elastically coupled circular cylinders in side-by-side arrangement is investigated numerically. The Reynolds-averaged Navier–Stokes equations are solved by the finite element method for simulating the flow and the equation of motion is solved for calculating the vibration. The mass ratio (the ratio of the mass of the cylinder to the displaced fluid mass) is 2 and the Reynolds number is 5000 in the simulations. Simulations are carried out for one symmetric configuration (referred to be Case A) and one asymmetric configuration (referred to be Case B). In both Case A and Case B, the primary response frequencies of the two cylinders are found to be the same both inside and outside the lock-in regimes. Five response regimes are found in both cases and they are the first-mode lock-in regime, the second-mode lock-in regime, the sum-frequency lock-in regime and two transition regimes. When the vibration is transiting from the first- to the second-mode lock-in regimes, the vibration of each cylinder contains both first- and the second-mode natural frequencies, and the vibrations are usually irregular. In the transition regime between the second-mode lock-in and the sum-frequency lock-in regimes, the response frequencies of both cylinders increases with an increase in the reduced velocity until they are close to the sum of the two natural frequencies. In both cases, the lower boundary reduced velocity of the total lock-in regime (the sum of the five lock-in regimes) is about 3 and the upper boundary reduced velocity is about 11 times the first-to-second-mode natural frequency ratio.

1. Introduction

Vortex-induced vibration (VIV) of circular cylinders immersed in fluid flow is of engineering significance. The very fundamental case of VIV is the vibration of an elastically mounted circular cylinder in flow and it has been studied extensively in the past two decades. Feng (1968) carried out a pioneering study of one-degree-of-freedom (1-dof) VIV of a circular cylinder in the cross-flow direction at high mass ratios, and found that the vortex shedding frequency locks into the natural frequency of the cylinder at the reduced velocity of 5 and remains locked-in until the reduced velocity is about 7. Therefore, the vortex shedding in the lock-in regime does not follow the Strouhal law. Williamson and Roshko (1988) reported that the vortex shedding frequency equals to the vibration frequency in the lock-in regime because the vortex shedding is forced to interact with the vibration of the cylinder. The lock-in regime of the VIV of a circular cylinder at low

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mass ratios was studied experimentally by Khalak and Williamson (1996, 1997, 1999) and Govardhan and Williamson (2000), and it was found that the lock-in regime at low mass ratios are wider than that at high mass ratios. Some numerical studies were also carried out and it has been shown that the two-dimensional numerical model can provide satisfactory prediction of VIV of an elastically mounted rigid cylinder (Anagnostopoulos and Iliadis, 1998; Anagnostopoulos 2000a,b; Guilmineau and Queutey, 2004; Pan et al., 2007; Kataoka, 2008; Zhao and Cheng, 2011; Zhao et al., 2012). Yang et al. (2008, 2009) carried out an experimental investigation of a cylinder near a rigid boundary in steady flow, and found that the amplitudes and frequencies of VIV have a close relationship with the gap-to-diameter ratio and the reduced velocity.

VIV of a pair of circular cylinders in fluid flow has been also studied extensively. Zdravkovich (1985) investigated VIV of two circular cylinders and found that the oscillation amplitude depends very strongly on the relative locations of the two cylinders. The numerical study by Mittal and Kumar (2004) on VIV of two circular cylinders in tandem for a distance between their centers equal to 5.5 cylinder diameters showed that the upstream cylinder responds as an isolated single cylinder while the downstream one undergoes disorganized motion. Wang et al. (2008) studied flow induced vibration of two flexible cylinders in a side-by-side arrangement. It was found that the free-stream turbulence enhanced the vortex-induced force, thus to restore the large amplitude vibration associated with the lock-in resonance. By carrying out laboratory experiments, Huera-Huarte and Gharib (2011a, 2011b) investigated vortex-induced vibration of two flexible cylinders in side-by-side and tandem arrangements. It was found that the interference between the two cylinders was very weak if the center-to-center gap exceeded 3.5 times the cylinder diameter in the side-by-side configuration. Rahmanian et al. (2012) simulated VIV of two mechanically coupled circular cylinders of different diameters at a diameter ratio of 0.1 and a fixed reduced velocity in the lock-in regime. They found that positioning a smaller cylinder close to the large one significantly changed the vibration mode and the response was affected by the position angle of the smaller cylinder. Zhao and Cheng (2012) studied VIV of four circular cylinders in a square configuration in steady flow numerically. It was found that the angle of incidence affects not only the vibration amplitude but also the lock-in regime of the reduced velocity.

In most of the studies about VIV of multiple cylinders, the cylinders are either rigidly coupled to each other or elastically mounted separately. In this study, VIV of elastically connected two side-by-side circular cylinders in steady flow as shown in Fig. 1 is studied numerically. The flow is simulated by solving the Reynolds-averaged Navier–Stokes (RANS) equations using the finite element method. The displacements of the cylinders are calculated by solving the equations of the motion of the system. Two scenarios are considered in this study. The symmetric configuration is referred to be Case A and the asymmetric configuration is referred to be Case B as shown in Fig. 1. The simulations are carried out for a wide range of reduced velocity that covers the whole lock-in regime. The response frequency and amplitude is analyzed.

2. Numerical method

2.1. Equation of motion

Two side-by-side elastically coupled circular cylinders are considered. The cylinders are placed in steady flow and allowed to vibrate only in the transverse direction of the flow. The two cylinders are of the same diameter and the same mass. Two configurations are considered as shown in Fig. 1. The symmetric configuration is referred to be Case A and the asymmetric configuration is referred to be Case B in the discussions. In each configuration, the stiffness of all the springs is K. The vibration system is of two-degree-of-freedom. In this study, the distance between the two cylinder centers is a constant of $L=3D$ with D being the diameter of the cylinders. The differential equations governing the vibration of the two-degree-of-freedom

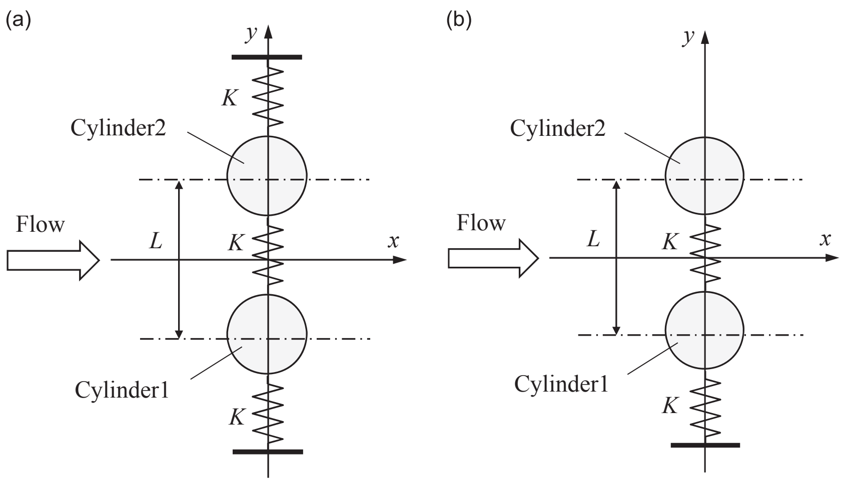

Fig. 1. Sketch of two elastically coupled side-by-side cylinders in flow.