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Lock-in study of two side-by-side cylinders of different diameters in close proximity in steady flow

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ABSTRACT

Lock-in of the vortex-induced vibration of two side-by-side circular cylinders of different diameters (diameter ratio $d/D=0.1$) is investigated numerically. The cylinders are located in close proximity and free to oscillate in the cross-flow direction. The initial gap between the two cylinders is set the same as the small cylinder diameter (d). The mass ratios of both cylinders (m) are fixed to be 5 and the damping ratios are small enough to be negligible. Simulations are first carried out for two cases where the large-to-small-cylinder natural frequency ratio is 1. Case 1 is focused on the lock-in of the large cylinder and Case 2 is focused on the lock-in of the small cylinder, which is far narrower than that of the large cylinder. Then simulations are carried out at a natural frequency ratio (small-to-large-cylinder) of 0.1, where both cylinders are expected to lock on to their own natural frequencies (referred to be Case 3). The interference between the two cylinders under these conditions is investigated in detail. The widening of the lock-in range of the reduced velocities for the large cylinder in Case 1, the beating behavior of the small cylinder in its lock-in range in Case 2 and the dual lock-in behavior of the small cylinder during the simultaneous lock-in of both cylinders in Case 3 are some of the key findings of this study.

1. Introduction

Vortex-induced vibrations (VIVs) occur in many aerodynamics and hydrodynamics applications. Structures such as tension leg platforms, drilling risers, catenary and submarine pipelines, transmission lines, chimneys and bridges experience vibrations induced by fluid flow passing across them. Excessive vibrations weaken the durability and shorten the lives of the structures. The qualitative and quantitative estimations of these vibrations are important for the evaluation of structural fatigue failure.

VIV of a cylinder in steady flow is governed by a number of important parameters including Reynolds number $\mathrm{Re}=U_\infty D/\nu$, mass ratio $m=m/m_d$, structural damping factor of the cylinder, $\zeta=\delta/2\pi$ and reduced velocity, $U_r=U_\infty/f_nD$, where U_∞ is the free stream velocity, D is the diameter of the cylinder, ν is the kinematic viscosity of the fluid, m is the mass of cylinder, m_d is the mass of displaced fluid by the cylinder, δ is the natural logarithmic decrement of the oscillating cylinder and f_n is the natural frequency of the system. For a stationary circular cylinder, the non-dimensional vortex shedding frequency is defined as the Strouhal number (St) by $\mathrm{St}=fD/U_\infty$, with f being the vortex shedding frequency. The consensus value of the Strouhal number is about 0.2 for a fixed circular cylinder in the subcritical Reynolds number regime

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(Williamson, 1996). The vortex shedding frequency of an elastically mounted circular cylinder follows the Strouhal law outside the lock-in (resonance) regime. However when the reduced velocity is within the lock-in regime, the vortex shedding frequency locks onto the vibration frequency of the cylinder instead of following the Strouhal law. It has been found that the lock-in occurs at a wide range of reduced velocity and results in very high vibration amplitudes Feng (1968).

Studies of the lock-in phenomena at high mass ratios (Feng, 1968; Brika and Laneville, 1993) and at low mass ratios (Khalak and Williamson, 1996, 1997, 1999) revealed the dependence of the dynamic response on the mass-damping ratio ($m\zeta$). The mass-damping ratio in the test of Khalak and Williamson (1996) was one order of magnitude less than that in the test by Feng (1968). Low mass-damping ratios result in wide lock-in regimes and high maximum oscillation amplitudes of the cylinder. Jauvtis and Williamson (2004) showed that allowing the cylinder to oscillate in 2-DOF also contributes to high amplitude of vibration provided that the mass ratio is less than 6. Zhao and Cheng (2010, 2011) compared numerical results with the experimental data by Jauvtis and Williamson (2004) and found that the numerical results agreed well with the experimental measurements. Transverse oscillations of an elastically mounted rigid cylinder in steady flow have been discussed by many researchers. Bearman (1984, 2011), Williamson and Govardhan (2004), Sarpkaya (2004) and Gabbai and Benaroya (2005) gave extensive reviews on the VIV of a circular cylinder.

Flow interference between two parallel cylinders occurs in many engineering problems and has been the subject of many studies. The arrangement of two parallel cylinders can be side-by-side, tandem, or staggered relative to the incoming fluid flow. Sumner (2010) reviewed extensively the available literature on fluid flow around two cylinders of equal diameters. According to Zdravkovich (1977, 1985), the interference between two cylinders occurs at three different patterns depending on the arrangement of the cylinders. Proximity interference occurs when the two cylinders are close to each other and placed side-by-side. Wake interference takes place if one of the cylinders is fully or partially submerged in the wake of another and the flow around it is significantly affected by the wake of the upstream cylinder. The third flow pattern is the overlapping of the proximity interference and the wake interference. The flow interferences can be bi-stable in some regions and cause high amplitude vibrations. The mechanisms of the resultant oscillating force coefficient by these interferences, jet-switch and gap-flow-switch were also discussed by Zdravkovich (1977, 1985).

Zdravkovich (1988) and Sumner et al. (1999) studied flow around two side-by-side cylinders at different gap ratios. They found that two side-by-side cylinders in contact with each other act in a similar way to a single bluff body. A single vortex street was identified in the downstream of the cylinders. The large vortices that are shed from the cylinders had irregular shapes and were disintegrated into small vortices. Two vortex shedding frequencies were found in the spectra of shed vortices. The PIV tests conducted by Sumner et al. (1999) in a water tunnel showed the variation of the vortex formation length. At small gap ratios ($G/D<0.2$) between two side-by-side cylinders, the single bluff body behavior changed slightly. A small gap between the two cylinders leads to a lower reduction of drag forces on both cylinders and more extended vortex formations length behind them. King and Johns (1976), Brika and Laneville (1999), Mittal and Kumar (2001), Assi et al. (2006), Alam et al. (2005) and Mahbub Alam and Kim (2009) are a few among many studies discussing the VIV of two identical circular cylinders in tandem and staggered arrangement. In an experimental study of VIV of two tandem cylinders, Assi et al. (2006) observed galloping and continuous increase of the vibration amplitude for the reduced velocity at $m=1$ and 2 with $3.0<S/D<5.6$, where S is the pitch distance between the two cylinders. Brika and Laneville (1999) found that the dominant vibration mechanism of both cylinders at large pitch distances and high mass ratios is VIV. The experimental and numerical studies by Dalton et al. (2001) on two cylinders with different diameters showed that both drag and lift forces on the large cylinder were reduced by purposely placing a small diameter cylinder in its wake. The small cylinder was found to weaken the vortex shedding from the large cylinder. Lee et al. (2012) studied the interaction and the wake structure behind two side-by-side cylinders with a diameter ratio of $D/d=2$ and a gap ratio of $0.75D$. Their experiments revealed the presence of two dominant lock-in frequencies in the wake region, namely the excitation frequency and its one-third sub-harmonics.

While the aforementioned studies on two cylinder wakes are mainly concerned on the force characteristics and flow regime classifications, the study on VIV of two side-by-side cylinders with different diameters is limited. This paper presents a study on the interference of two cylinders undergoing VIV. The cross flow vibrations of two elastically mounted side-by-side circular cylinders of different diameters in a steady current are the focus of this study. Individual and mutual lock-in and potential collisions of the two cylinders are investigated.

Although three-dimensional models are preferable for investigating flow interaction between cylinders, the computational cost of three-dimensional study at high Reynolds numbers is prohibitively high. The use of a two-dimensional numerical model in this study is actually a compromise between computational efficiency and numerical accuracy. The efficiency of two-dimensional models enables a systematic study covering a wide range of parameters at affordable computational costs. They have been applied successfully to simulate various VIV problems over a wide range of Reynolds numbers, e.g., Cox et al. (1998), Guilmineau and Queutey (2004), Mittal and Kumar (2004), Wanderley et al. (2008) and Ding et al. (2013).

2. Problem description

The schematic diagram of two side-by-side circular cylinders free to oscillate in the cross flow direction is shown in Fig. 1. The ratio of the small cylinder diameter to the large one (d/D) is fixed as 0.1. The initial gap between the two cylinders is equal to the small cylinder diameter ($G=d$). The incoming flow is steady and is in the horizontal direction as shown in Fig. 1.