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Numerical study of flow-induced oscillations of two rigid plates elastically hinged at the two ends of a stationary plate in a cross-flow

Masoud Darbandi *, Nematollah Fouladi

Center of Excellence in Aerospace Systems Department of Aerospace Engineering, Sharif University of Technology, Azadi Ave., P. O. Box 11365-8639, Tehran, Iran

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ABSTRACT

The flow-induced oscillation (FIO) of bluff bodies is commonly encountered in the fluid structure interaction (FSI) problems. In this study, we use an unstructured moving grid strategy and simulate the FIO of two rigid plates, which are elastically hinged at the two ends of a fixed flat plate in a cross-flow. We use a hybrid finite-element-volume (FEV) method in an arbitrary Lagrangian–Eulerian (ALE) framework to study FIO of the two hinged plates. The current simulations are carried out for wide ranges of flow Reynolds number (50–175), spring stiffness coefficient, and the two hinged plates' moment of inertia magnitudes. The influences of these parameters are investigated on the magnitudes of maximum deflection angle, the amplitude of oscillation, the total lift and drag coefficients, and so on. The study is also carried out in the transition period to describe the in-phase and out-of-phase angular oscillations occurring for the two elastically hinged plates with respect to each other. After the transition period, the two hinged plates eventually arrive to a similar periodic oscillation; however, with some phase lags. We find that the achieved phase lag is equal to the phase lag between the two pairs of flow vortices, which are alternatively shed into the flow from the upper and lower hinged plates. Similar to past FIO problems, the current model also exhibits two important lock-in and phase-switch FSI phenomena; however, in angular directions. There is a phase jump of approximately 170° between the aerodynamic lift coefficient and angular oscillations of hinged plates, which nearly occurs in the middle of lock-in region. Indeed, our literature review shows that this is the first time to report the phase-switch phenomenon in angular oscillations of three-element bluff bodies in a FSI problem.

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1. Introduction

The fluid–structure interaction (FSI) problems are widely encountered in many industrial sciences such as mechanical, aerospace, biomedical, marine, and wind engineering applications (Pahlke and van der Wall, 2005; Zhang and Suzuki, 2007; Vigmostad et al., 2010). The flow-induced oscillation (FIO) is one of the most frequently researches, with considerable

* Corresponding author.
E-mail address: darbandi@sharif.edu (M. Darbandi).
URL: https://sharif.edu/~darbandi (M. Darbandi).

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attentions in studying the FSI problems. There are different dynamic and flow behaviors between a movable (or deformable) bluff body and the flow passing over it. These behaviors are widely influenced by the vortex shedding structure behind the bluff body. Ignoring the solid body vibration or oscillation, the FIO problem is simplified to the flow over a fixed bluff body, which may encounter unsteady flow behaviors under some specific conditions. In such cases, the flow vortices, originating from the body surface, are repeatedly shed into the downstream of bluff-body. Among many different investigated cases, the vortex shedding behind a stationary circular cylinder is the most studied. The Strouhal number is an important influential parameter to characterize the resulting oscillatory flows and is defined as $St = f_s L/U_\infty$, in which f_s is the frequency of vortex shedding, L is a characteristic length of bluff-body, and U_∞ is the freestream velocity. The literature contains numerous publications on the flow about the circular cylinder and other bluff bodies, where investigators use typically either experimental (Norberg, 1994,Wu et al., 2004) or numerical (Fernando and Modi, 1990; Saha, 2007; Perumal et al., 2012) tools to describe the physics of flow, the formation and tracking of vortices, and the effects of oscillations on aerodynamic/hydrodynamic performance.

Besides the vortex shedding behind the fixed bluff-bodies, there are many applications, in which the bluff body is forced to oscillate with a given frequency, say forced frequency (Bearman, 1984; Jeon and Gharib, 2004; Kocabiyik and Al-Mdallal, 2005; Singh et al., 2009; Ayache et al., 2010). Depending on the forced frequency magnitude, the vortex shedding mechanism may reveal interesting behaviors. For example, the interaction between the forced and vortex shedding frequencies can result in a phenomenon known as synchronization or lock-in. In this phenomenon, the vortex shedding frequency approaches the forced frequency and yields interest physics. Bishop and Hassan (1964) investigated experimentally the effect of forced frequency on the flow vortex shedding mechanism behind a circular cylinder and reported the resulting synchronization behavior. They showed that the phase angle between the transverse force and the body movement would change abruptly if the forced frequency approached the natural frequency of vortex shedding. This phenomenon is known as the phase-jump or phase-switch. They attributed this behavior to the sign change in energy transfer between the fluid flow and the oscillating body. More exploration on this phenomenon has been the subject of many other works since then. Zdravkovich (1982) described the phase-jump from another aspect and attributed it to the change in vortex formation mechanism and its shedding behavior. Ongoren and Rockwell (1988) emphasized that the phase-jump exhibition would depend on the bluff body geometry. They indicated that this exhibition may not be observed for bluff bodies with a significant after-body. Blackburn and Henderson (1999) investigated numerically the forced oscillations on a circular cylinder. They stated that the phase-jump would occur as a result of the competition between two different vortex formation mechanisms.

Most of past studies in the forced bluff-body oscillation problems have been focused on either transverse or in-line oscillations, with respect to the free stream direction (Bishop and Hassan, 1964; Zdravkovich, 1982; Bearman, 1984; Ongoren and Rockwell, 1988; Blackburn and Henderson, 1999; Jeon and Gharib, 2004; Kocabiyik and Al-Mdallal, 2005; Ponta and Aref, 2006; Al-Mdallal et al., 2007; Singh et al., 2009; Ayache et al., 2010; Sai and Chuanping, 2012). There are relatively few studies to analyze the bluff-bodies with forced rotational oscillations. Furthermore, many rotational oscillation studies have chosen the circular cylinder as their bluff body (Lu and Sato, 1996; Baek and Sung, 2000; Fujisawa et al., 2005; Nazarinia et al., 2012). Indeed, there are rare investigations to pay attention to forced rotational oscillations of flat plates. For example, Vial et al. (2004) and Chen and Fang (2005) have provided either experimental or numerical evidences to show the appearance of lock-in behavior for one flat plate under forced rotational oscillations.

As known, the flow vortex shedding can induce oscillatory aerodynamic/hydrodynamic loads on the bluff body surface and this can consequently result in the bluff body oscillations. Similar to the bluff-body forced oscillation problems, the lock-in and phase-jump phenomena have been observed and reported in a few past FIO investigations. They indicate that the largest bluff-body amplitude of oscillation would occur within the lock-in region, where the frequency of vortex shedding is close to the frequency of bluff body oscillations. Literature shows that most of past researchers have chosen the circular cylinder as their bluff body to investigate the FIO of bluff body (King, 1977; Goswami et al., 1993; Zhou et al., 1999; Leonard and Roshko, 2001; Facchinetti et al., 2004; Li et al., 2009; Bearman, 2011). Meanwhile, there has been relatively much less attention to the FIO of flat plats (Gomes et al., 2010, Yang and Stern, 2012), and especially to the cases with rotational vibrations.

Irrespective of the above brief literature review, the huge number of past publications in flow over and across a flat plate indicates that the case of a single flat plate has been largely investigated by the industrial and academic researchers. Most probably, it is because this simple model can readily represent many complex industry applications with real phenomena. Among various bluff-body cases, a sharp-edge flat plate would perform the largest bluffness effects in a cross-flow. Therefore, the flow would become unsteady in very low Reynolds numbers in such case. On the other hand, the flow parameters such as the time variation of static pressure would exhibit very rapid changes for this bluff body comparing with the cylinder-type bodies at the same Reynolds number. Such rapid pressure changes can result in the FIO of this bluff body at very low Reynolds numbers. Evidently, this would also cause more relatively energetic flow-body interactions. Considering such anticipated phenomena, we construct a new configuration consisting of one fixed and two identical rotatable flat plates. The rotatable flat plates are elastically hinged at the two ends of the fixed plate and the assembly is subject to a cross-flow, see Fig. 1. The lower and upper rigid plates are hinged to the fixed plate supporting by two similar torsional spring-damper systems. Therefore, each of the two hinged plates has only one rotational degree of freedom, i.e., they can only rotate around their hinges. The two plates can oscillate around their pivoting points due to the vortex shedding influences. This configuration is suitable to study the large induced rotational behaviors of hinged plates at low Reynolds

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