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Numerical study of the suppression mechanism of vortex-induced vibration by symmetric Lorentz forces

Hui Zhang*, Bao-chun Fan, Zhi-hua Chen, Hong-zhi Li

Science and Technology on Transient Physics Laboratory, Nanjing University of Science and Technology, Nanjing 210094, China

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ABSTRACT

In this paper, the electro-magnetic control of vortex-induced vibration (VIV) of a circular cylinder is investigated numerically based on the stream function–vorticity equations in the exponential–polar coordinates attached on the moving cylinder for Re = 150. The effects of the instantaneous wake geometries and the corresponding cylinder motion on the hydrodynamic forces for one entire period of vortex shedding are discussed using a drag–lift phase diagram. The drag–lift diagram is composed of the upper and lower closed curves due to the contributions of the vortex shedding but is magnified, translated and turned under the action of the cylinder motion. The Lorentz force for controlling the vibration cylinder is classified into the field Lorentz force and the wall Lorentz force. The symmetric field Lorentz force will symmetrize the flow passing over the cylinder and decreases the lift oscillation, which, in turn, suppresses the VIV, whereas the wall Lorentz force has no effect on the lift. The cylinder vibration increases as the work performed by the lift dominates the energy transfer. Otherwise, the cylinder vibration decreases. If the net transferred energy per motion is equal to zero, the cylinder will vibrate steadily or be fixed.

1. Introduction

Fluid–structure interactions occur in many engineering fields. These interactions give rise to complicated vibrations of the structures and can cause structural damage under certain unfavorable conditions. For a cylinder mounted on flexible supports, the fluctuating forces induced by changing vortex shedding cause the cylinder to vibrate. Next, the vibrating cylinder alters the flow field, which, in turn, changes the flow-induced force. The vibration of the cylinder can increase still further until a limiting behavior is reached. This vortex-induced vibration (VIV) phenomenon is a basic and fundamental problem.

Representative experimental studies on VIV include those of Feng (1968), Griffin (1980), Griffin and Ramberg (1982), Brika and Laneville (1993), Hover et al. (1997) and Griffin and Koopmann (1977), in which classic lock-in was observed, whereas the shedding frequency coincided with the natural structure frequency. The cylinder experiences significant vibration only with lock-in, and the vibration amplitude has a strong relationship with the phase difference between the lift force and the cylinder motion. However, recently, the experimental results of Gharib et al. (1997), Gharib (1999) and Khalak and Williamson (1997) provided examples of significant flow-induced vibration without lock-in and suggested that the

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* Corresponding author.
E-mail address: zhanghui1902@hotmail.com (H. Zhang).

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lock-in of VIV is dependent on the values of the cylinder/fluid mass ratio. Recently, Franzini et al. (2009), Lam and Zou (2010) and Korkischko and Meneghini (2010) focused on the interaction of multiple cylinders. It was found that the gap or arrangement has a significant effect on the response of the VIV system. Moreover, the experimental results of flow around a circular cylinder with moving surface boundary layer control (MSBC) have been presented, and MSBC has the advantages of drag reduction and vibration suppression (Korkischko and Meneghini, 2012).

Various numerical approaches have also been proposed to treat the fully coupled problem involved with VIV. Typically, these approaches can be divided into two broad categories. For one category, the Navier–Stokes equations are solved directly, such as the direct numerical simulation (Newman and Karniadakis, 1997; Evangelinos and Karniadakis, 1999; Evangelinos et al., 2000), the spectral element spatial method (Blackburn and Henderson, 1996; Blackburn et al., 2001) and the finite element method (Mittal and Kumar, 1999; Mendes and Branco, 1999; So et al., 2001). For the other category, the flow field is obtained by solving the vorticity transport equations, where the usual assumption is a two-dimensional laminar flow, such as the vortex-in-cell (VIC) method (Slaouti and Stansby, 1994; Zhou et al., 1999) and the viscous-vortex method (Shiels et al., 2001; Leonard and Roshko, 2001). It has been shown from these studies that in a great majority of cases, the response is essentially sinusoidal. The lock-in phenomenon has been studied, and the vortex-induced vibrations on a circular cylinder and the associated phenomena, such as the response of the cylinder, the unsteady lift and drag on the cylinder, the vortex shedding frequency and the effects of the cylinder motion on the vortex structure in the wake, have been examined further. Recently, numerical simulation for the interaction of multiple cylinders was also performed (Wang et al., 2008; Lam and Zou, 2010; Huera-Huarte and Gharib, 2011; Anagnostopoulos and Dikarou, 2011; Zhao and Cheng, 2012). Moreover, two-degrees-of-freedom vortex-induced vibrations of a circular cylinder close to a plane boundary have been investigated (Mittal and Kumar, 1999; Zhao and Cheng, 2011).

The progress made during the past two decades on VIV has been reviewed (see e.g., Williamson and Govardhan, 2004; Sarpkaya (2004)). It is clear that the investigation of fluid–structure interactions as a fully coupled problem is far from complete, and there still remain some uncertainties, such as added mass, force decomposition and their effects on the characteristics of fluid–structure systems. Moreover, the sinusoidal function of force and response is approximate, which has been discussed by Williamson and Govardhan (2004). The coupling between the motion of the cylinder and the flow is provided by the parameters. Therefore, more investigations on the coupling by the derivation of hydrodynamic forces are necessary.

In addition, the control of VIV has many practical applications in the engineering point of view, but a little work has been performed with other approaches (Gattulli and Ghanem, 1999; Owen et al., 2001; Korkischko and Meneghini, 2012). However, the control of VIV by Lorentz force (decomposed into the field Lorentz force and the wall Lorentz force) has not been discussed in the open literature.

Electro-magnetic control is considered to be one of the most practical methods to manipulate the flow (Tang and Aubry, 1997; Berger et al., 2000; Breuer et al., 2004; Mutschke et al., 2006; Braun et al., 2009). Regarding the flow past a fixed circular cylinder, Crawford and Karniadakis (1995) investigated the effects of Lorentz force on the elimination of flow separation numerically. Weier et al. (1998) confirmed the suppressing effect of Lorentz force via both experiments and calculations. Kim and Lee (2001) and Posdziech and Grundmann (2001) found that both the continuous and pulsed Lorentz forces can suppress the lift oscillation and stabilize the flow. The closed-loop and optimal control methods were developed to improve its control efficiency in our research group (Zhang et al., 2010a,b, 2011), and the suppression of VIV by symmetric Lorentz force has also been preliminarily investigated (Chen et al., 2007).

The problems discussed in the paper are described by the stream function–vorticity equations in the coordinates attached on a moving cylinder, coupled with the cylinder motion equation via the hydrodynamic force exerted on the cylinder surface. The initial and boundary conditions for this moving stream function–vorticity system are derived. Moreover, the hydrodynamic forces are formulated mathematically and consist of the vortex-induced force, the inertial force, the viscous damping force and the force induced directly by the wall Lorentz force. It is worth noting that the viscous damping force providing the viscous contribution to damping cylinder vibration is usually neglected in some earlier publications because of the widely accepted Lighthill's force decomposition. In addition, the added mass generated due to the body acceleration, one of the most confused parameters in mathematical expressions, has also been established by the assumption of a sinusoidal response, which consists of the potential added mass and the apparent added mass, which correspond to the effects of inviscid flow and viscosity, respectively. Finally, the phase angles among the cylinder displacement, the total lift force and the vortex-induced lift force are formulated.

The abovementioned complete systems for a fully coupled fluid–structure interaction problem are calculated numerically in the paper. Using these systems, the VIV phenomenon with or without control can be described by the calculated instantaneous wake geometries and the corresponding cylinder motion as well as the hydrodynamic force distributed on the cylinder surface in one entire periodic of vortex-shedding. Furthermore, the mechanisms of fluid–cylinder interactions and electro-magnetic controls are discussed in detail. In addition, a drag–lift phase diagram is also employed, which not only denotes the corresponding fluctuation of the drag and lift over a complete time period but also implies the detailed information of the flow patterns.

The evolution of VIV, starting from rest and subsequently undergoing development and suppression, is presented in the paper. The variations of some characteristics of the fluid–structure interaction of VIV in this evolution process, such as displacement and amplitude of VIV cylinder, in-phase and out-of-phase components of the fluid force, phase angle between the lift force and the cylinder displacement, added mass, transferred energy, lift and drag etc., are discussed. It is