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Flow-induced vibration on a circular cylinder in planar shear flow

Jiahuang Tu [a], Dai Zhou [a,b,c,*], Yan Bao [a,d], Congqi Fang [a], Kai Zhang [a], Chunxiang Li [e], Zhaolong Han [a,f]

[a] Department of Civil Engineering, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, No. 800, Dongchuan Road, Shanghai 200240, China
[b] State Key Laboratory of Ocean Engineering, Shanghai Jiaotong University, Shanghai, China
[c] Institute of Oceanology, Shanghai Jiao Tong University, Shanghai, China
[d] Department of Aeronautics, Imperial College London, London SW7 2AZ, UK
[e] Department of Civil Engineering, Shanghai University, 99 Shangda Road, BaoShan District, Shanghai 200444, China
[f] Cullen College of Engineering, University of Houston, Houston, TX 77204, USA

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ABSTRACT

In this paper, the flow-induced vibrations of an elastically mounted circular cylinder subjected to the planar shear flow with the 1-DOF (only transverse direction) and 2-DOF (in-line and cross-flow directions) movements are studied numerically in the laminar flow (Re = 150). Based on a characteristic-based-split (CBS) finite element method, the numerical simulation is conducted, and is verified through the benchmark problem of the uniform flow past an elastically mounted circular cylinder. The computation is carried out for lower reduced mass of $M_r = 2.0$ and the structural damping ratio is set to zero to maximize the vortex-induced response of the cylinder. The effects of some key parameters, such as shear rate ($k = 0.0$–0.1), reduced velocity ($U_r = 3.0$–12.0) and natural frequency ratio ($r = 1.0$–2.0), on the characteristics of vortex-induced vibration (VIV) responses are studied. The results show that, in the 1-DOF system, the frequency synchronization region extends with the increasing of k. The shear rate greatly affects the phase portraits, which shift from the double-valued type to the single-valued one. On the other hand, in the 2-DOF system, the increasing of k causes the extension of the single-resonant region and dual-resonant one at the lower natural frequency ratios. While at the higher natural frequency ratios, the change of k only expands the single-resonant region in the transverse direction. The predominant vortex shedding patterns are 2S and P + S modes. Finally, the interaction between vortex and cylinder as well as the mechanism of flow-induced vibration in planar shear flow are revealed. The phase between the force and its corresponding displacement changes from out-of-phase to in-phase and the higher harmonic forces appear with the increasing of shear rate, resulting in the energy transferring from the fluid to the structure and then the dynamic response of the cylinder intensifying.

1. Introduction

Many engineering applications, such as bridge structures, offshore structures and ocean structures to name a few, are plagued by the vortex-induced vibration problem. In the recent years, a considerable number of studies have been summarized in comprehensive reviews [1–4]. However, most of these published literatures are concentrated on the VIV of the cylindrical structure exposed to the uniform flow. In the practical cases, both air and ocean currents have velocity gradients in space, regarded as the axial shear flow and planar shear flow. Hence, the structure is immersed in the non-uniform flow rather than uniform. The difference in velocity between the top and bottom of the body causes a complicated interaction with the boundary layers that separate from the body which results in different vortex shedding structures, as reported by Cheng et al. [5,6]. The free-stream with a linear velocity profile, $u_x = U_c + ky$, over a circular cylinder is illustrated in Fig. 1. The dimensionless flow parameters of Reynolds number Re and the shear rate k are defined as, $Re = U_cD/\nu$ and $k = GD/U_c$, where U_c is the centerline velocity, D the characteristic length, ν the kinematic viscosity of the fluid, and G the velocity gradient of the shear flow [7–10].

So far, many studies about the planar shear flow past a stationary cylinder structure have been reported in the available literatures. They mainly focused on the influences of the shear parameters on the aerodynamic forces, vortex shedding frequency, and vortex structure behind a bluff body in the shear flow. In the previous experimental studies, some researchers put emphasis

* Corresponding author at: School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, No. 800 Dongchuan Road, Minhang District, Shanghai 200240, China. Tel.: +86 21 34206195; fax: +86 21 34206198.
E-mail address: zhoudai@sjtu.edu.cn (D. Zhou).

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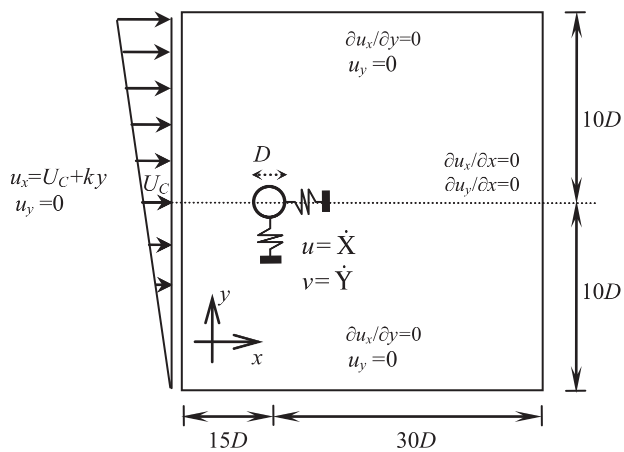

Fig. 1. Computational model of 2-DOF VIV and computational domain size.

on the effect of shear rate on the frequency of vortex shedding from a circular cylinder [7,8,11,12]. Kiya et al. [7] and Kwon et al. [8] claimed that the Strouhal number increased with increasing shear rate. However, Cao et al. [11] and Summer and Akosile [12] reported that the vortex shedding frequency kept a constant despite the change of shear rate at the subcritical Reynolds number. They explained that the effects of the blockage ratio and Reynolds number resulted in the different trends of the vortex shedding frequency. On the other hand, a number of studies have been performed on the shear flow over a circular cylinder by means of numerical methods. Lei et al. [9] and Kang [13] asserted that the Strouhal number slightly decreased or remained unchanged with the increasing of shear rate at the lower Reynolds numbers. In addition, there are some numerical simulations focused on the square cylinder subjected to the shear flow [5,6,10,14]. Saha et al. [10] presented that a study of planar shear flow past a square cylinder with different shear ratios ($0.0 \leqslant k \leqslant 0.2$) in the turbulent flow regime. They pointed out that the vortex shedding frequency decreased with the increasing of shear rate, and the vortex street behind the bluff body disappeared at larger shear rate. The similar results were also reported by Cheng et al. [5,6] in the laminar flow region. Lankadasu and Vengadesan [14] investigated the shear flow field around a two-dimensional square cylinder with the shear rate ranged from 0.0 to 0.2 at much lower Reynolds numbers. They pointed out that the critical value of the Re exists between 42 and 43, at $k = 0.1$, whereas at $k = 0.2$, the critical Re lies between 38 and 40. Recently, Cao et al. [15–17] conducted some simulations of the 3-D circular, square and rectangular cylinder immersed in the shear flow using both direct numerical simulation and large eddy simulation methods. In their work, the variations of the Strouhal number, force coefficients and vortex street structures with the shear rate in a wide range of Reynolds number ($60 \leqslant \mathrm{Re} \leqslant 22{,}000$) were presented.

Several researchers have concentrated on the VIV for the uniform flow case at both low and high Reynolds numbers (see Assi et al. [18], Borazjani and Sotiropoulos [19], Dahl et al. [20–22], Sanchis et al. [23], He et al. [24]). Williamson and Roshko [25] observed that the effect of vortex shedding on the cylinder motion was significant; and the vortex shedding frequency matched the structural frequency in the lock-in region. The phenomenon of soft lock-in was defined by Mittal and Kumar [26,27], where the frequency of vortex shedding was not consistent with the body motion frequency, whereas a larger amplitude was obtained for the low mass ratio case. Lucor and Triantafyllou [28] performed a numerical simulation of the single cylinder subjected to the 2-DOF VIV for a wide range of transverse natural frequency within the synchronization region. They pointed out that the synchronization region broadened with the increasing of frequency ratio. Dahl et al. [22] and Bao et al. [29] also found the 'dual-resonance' phenomenon of an isolated circular cylinder exposed to the uniform flow in the turbulent flow and laminar flow, respectively.

More recently, some researches about VIV of the elastically mounted circular cylinder immersed to the planar shear flow have been done through numerical methods. Singh and Chatterjee [30] performed a numerical investigation on the VIV of an isolated circular cylinder exposed to the linear shear flow at low Reynolds numbers ($70 \leqslant \mathrm{Re} \leqslant 500$). Zhang et al. [31] discussed the effects of shear ratio and added mass on the characteristics of the fluid–structure interaction of 1-DOF VIV for the single circular cylinder in the laminar flow region.

However, a comprehensive investigation, as far as known to us, on the1-DOF and 2-DOF VIV for an isolated circular cylinder in the planar shear flow has not been done yet. In this investigation, we present the numerical simulations for the VIV characteristics of an isolated circular cylinder immersed in the planar shear flow with different shear ratios. The aim of this study is to explore the effects of some parameters, such as shear rate (k), reduced velocity (U_r) and natural frequency ratio ($r = f_{nx}/f_{ny}$), on the characteristics of VIV response and the wake pattern behind the cylinder, and to contribute to understanding the mechanism of VIV for the circular cylinder subjected to the planar shear flow in the laminar flow region.

In this paper, the governing equations for incompressible flow and the motional equation of rigid bodies undergoing the in-line and transverse oscillations are described simply first, followed by detailed validations. Then, the computational results of both transverse-only and coupled cross-flow/in-line VIV for the single circular cylinder under the shear flow are analyzed in detail. The influences of some parameters, including shear rate, reduced velocity and natural frequency ratio, on the dynamic response and vortex shedding pattern are also elucidated. Finally, we analyze the flow-induced oscillation mechanism underlying the dynamics response of the cylinder in the planar shear flow.

2. Governing equations and numerical methods

2.1. Governing equations

The incompressible fluid flow is governed by the non-dimensional Arbitrary–Lagrangian–Eulerian (ALE) scheme of the Navier–Stokes equations [32,33], which can be written as follows:

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial u_i}{\partial t} + c_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{\mathrm{Re}} \frac{\partial^2 u_i}{\partial x_j \partial x_j}, \tag{2}$$

where u_i (or u_j) is the velocity component in the x_i (or x_j) coordinate direction and p is the pressure. The convective velocity is $c_j = u_j - \upsilon_j$, where υ_i is the ith component of the grid velocity vector.

The non-dimensional scheme of 2-DOF dynamic equations of an elastically mounted cylinder modeled by a mass-spring system read as follows:

$$\ddot{X} + \frac{4\pi\xi}{U_{rx}}\dot{X} + \frac{4\pi^2}{U_{rx}^2}X = \frac{C_D}{2M_r}, \tag{3}$$

$$\ddot{Y} + \frac{4\pi\xi}{U_{ry}}\dot{Y} + \frac{4\pi^2}{U_{ry}^2}Y = \frac{C_L}{2M_r}, \tag{4}$$

where $\ddot{X}, \dot{X}$ and X denote the in-line acceleration, velocity and displacement of the cylinder, respectively; while $\ddot{Y}, \dot{Y}$ and Y represent the same quantities corresponding to the transverse motion;