Journal of Fluids and Structures 59 (2015) 224–251

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Flow-induced vibrations of two circular cylinders in tandem with shear flow at low Reynolds number

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ARTICLE INFO

Article history:
Received 21 August 2014
Accepted 21 August 2015
Available online 26 October 2015

Keywords:
Vortex-induced vibration (VIV)
Planar shear flow
Shear rate
Two tandem cylinders
Four-step semi-implicit Characteristic-based split (4-SICBS)

ABSTRACT

The flow-induced vibrations of two elastically mounted circular cylinders subjected to the planar shear flow in tandem arrangement are studied numerically at Re = 160. A four-step semi-implicit Characteristic-based split (4-SICBS) finite element method is developed under the framework of the fractional step method to cope with the vortex-induced vibration (VIV) problem. For the computational code verification, two benchmark problems are examined in the laminar region: flow-induced vibration of an elastically mounted cylinder having two degrees of freedom and past two stationary ones in tandem arrangement. Regarding the two-cylinder VIVs in shear flow, the computation is conducted with the cylinder reduced mass $M_r = 2.5\pi$ and the structural damping ratio $\xi = 0.0$. The effects of some key parameters, such as shear rate ($k = 0.0, 0.05, 0.1$), reduced velocity ($U_r = 3.0$–18.0) and spacing ratio ($L_x/D = 2.5, 3.5, 4.5, 8.0$), are demonstrated. It is observed that the shear rate and reduced velocity play an important role in the VIVs of both cylinders at various center-to-center distances. Additionally, in comparison with the single cylinder case, a further study indicated that the gap flow has a significant impact on such a dynamic system, leading it to be more complex. The results show that, the performances of 'dual-resonant' are discovered in the shear flow. A valley is formed in transverse oscillation amplitude of DC for each spacing ratio when U_r is about 6.0. For the X–Y trajectories of the circular cylinders, figure-eight, figure-O and oval shape are obtained. Finally, the interactions between cylinders are revealed, together with the wake-induced vibration (WIV) mechanism underlying the oscillation characteristics of both cylinders exposed to shear flow. Besides, the "T+P" wake pattern is discovered herein.

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http://dx.doi.org/10.1016/j.jfluidstructs.2015.08.012
0889-9746/

1. Introduction

The problem of vortex-induced vibration can be encountered in many engineering applications, such as bridges, offshore structures and marine platforms to name a few. In the past few decades, the subjects of flow characteristics and flow-induced vibration on the multiple-cylinder system with circular section are hot research topics, which have attracted the interest of many researchers and a considerable number of studies have been summarized in comprehensive reviews (Zdravkovich, 1977; Sarpkaya, 2004; Sumner, 2010; Bearman, 2011). Some study fields, e.g. two 1-DOF circular cylinders (Borazjani and Sotiropoulos, 2009), two 2-DOF circular cylinders (Papaioannou et al., 2008), four 2-DOF circular cylinders with square arrangement (Zhao and Cheng, 2012), 1-DOF circular cylinder behind a stationary front circular cylinder (Lai et al., 2003) and 2-DOF circular cylinder behind a stationary front square cylinder (Han et al., 2014a), are widely reported.

However, most of these published literatures are concentrated on the VIV of the cylindrical structure exposed to the uniform flow. So far, several studies regarding the non-uniform flow past a single cylinder (Lu et al., 1997; Cheng et al., 2005; Kang, 2006; Cao et al., 2012) or two cylinders (Akosile and Summer, 2003; Bhattacharyya and Dhinakaran, 2008; Lankadasu and Vengadesan, 2008) have been carried out by both numerical simulations and experimental techniques. They pointed out that the influences of the shear parameter on the aerodynamic forces, vortex shedding frequency and flow pattern are of significance under the planar shear flow. Additionally, the dynamic responses of the cylinder are exposed to the non-uniform flow are more complex (Zhao et al., 2012; Lin et al., 2013; Singh and Chatterjee, 2014; Zhang et al., 2014; Tu et al., 2014).

The basic two-cylinder configurations in cross-flow are tandem (in-line), side-by-side (cross-flow) or staggered, while the gap spacing between the cylinders and Reynolds number are the key parameters that determine the wake flows. For the stationary tandem case, a critical spacing ratio (L_x/D, where L_x is the center-to-center spacing between the two cylinders and D the cylinder diameter) is between 3.5 and 4.0 in which the type of flow interference changes in the laminar region (Sharman et al., 2005; Papaioannou et al., 2008; Lin et al., 2013). At smaller spacing ratio, the two cylinders act like a single body and vortices only occur in the wake of the downstream cylinder. When L_x/D is beyond the critical ratio, the vortex shedding can be found in the gap between the cylinders.

On the other hand, a number of studies about the flow-induced vibration of two elastically mounted circular cylinders subjected to the uniform flow in various arrangements have been completed through experimental and numerical approaches in the last several decades. The effects of some parameters, such as spacing ration (L_x/D), reduced mass (M_r), reduced velocity (U_r) and natural frequency ratio ($r=f_{nx}/f_{ny}$), on the dynamic response and the characteristic of flow field were observed in both the laminar and turbulent flows in the available literature. When the frequency of vortex shedding approaches the nature frequency of the cylinder (f_n), the cylinder occurs large amplitude oscillation, called the phenomenon of "lock-in" (Langre, 2006). Additionally, when the spacing ratio between bluff bodies is higher than a threshold value, the flow interference characteristic changes from proximity-interference to wake-interference with the increasing of the spacing ratio and the downstream cylinder (DC) is affected by the wake of the upstream one (UC), as reported in Papaioannou et al. (2008) and Huera-Huarte and Bearman (2011).

The VIVs of two circular cylinders in different arrangements have been carried out by Zdravkovich (1985). Three categories of the cylinders motions were summarized, and for the tandem case, the amplitude of the downstream cylinder was larger than that of the upstream one in most cases.

Mittal and his team members carried out numerical simulations in which the center-to-center separation between two circular cylinders was as large as 5.5D (Mittal and Kumar, 2001; Prasanth and Mittal, 2009a, 2009b) and drew the conclusions that the performances of the upstream cylinder was similar to that of a single one, but the downstream cylinder showed significantly larger amplitude in the transverse direction. This is because the vortices shed from the front cylinder are well developed and attack the rear cylinder as the spacing was sufficiently large, giving rise to its stronger oscillations. Lock-in and hysteresis phenomena were observed for both the upstream and downstream cylinder.

Papaioannou et al. (2008) investigated the influences of gap spacing and reduced velocity on the vortex-induced vibration of two tandem cylinders with Re=160, M_r=10 and damping coefficient ξ=0.01 using the numerical method. Three cases of spacing ratios (L_x/D=2.5, 3.5, 5.0) were reported, respectively. In comparison with an isolated cylinder case, the dynamic motions of the bodies and flow field were more complex.

Borazjani and Sotiropoulos (2009) reported the flow characteristics of two tandem VIV cylinders having both one and two degrees of freedom at a small spacing ratio L_x/D=1.5, and concluded that the initial excitation mechanisms were dominated by the vortex-shedding pattern at low reduced velocities, but as it became higher, the gap-flow mechanism would provide the power for the shedding vortices. This kind of wake flow can be categorized as proximity-wake interference.

Bao et al. (2012) conducted a numerical investigation on the vortex-induced vibration of two oscillating cylinders in the tandem arrangement with different natural frequencies at L_x/D=5.0. They pointed out that the dynamic characteristic of the upstream cylinder was similar to that of a single cylinder, whereas that of the downstream cylinder was greatly affected by the upstream wake. In addition, the in-line dynamic response was more sensitive to the natural frequency ratio than the response in the transverse direction.

Lin et al. (2014) numerically studied the effects of spacing ratio, reduced mass and reduced velocity on the transversely oscillating cylinders in tandem. The biased oscillation region was observed in the area of large U_r, small L_x/D as well as low M_r at subcritical Re.