International Journal of Heat and Fluid Flow 65 (2017) 220–245

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

On characteristics of two-degree-of-freedom vortex induced vibration of two low-mass circular cylinders in proximity at low Reynolds number

Meng-Hsuan Chung

Department of Naval Architecture and Ocean Engineering, National Kaohsiung Marine University, No.142, Haijhuan Rd., Nanzih District, Kaohsiung City 811, Taiwan, ROC

A R T I C L E I N F O

Article history:
Received 10 May 2016
Revised 23 December 2016
Accepted 18 January 2017
Available online 2 February 2017

Keywords:
Vortex induced vibration
Stagger angle
Center-to-center spacing
Low Reynolds number
Low mass ratio
Cartesian grid method

A B S T R A C T

Two-degree-of-freedom vortex induced vibrations (VIVs) of two identical spring-supported circular cylinders in proximity with the mass ratio of 2 and zero damping at *Re* of 100 are numerically studied. Totally 20 arrangements of cylinders are investigated combining four stagger angles and five normalized center-to-center spacings. Results show that the in-line vibration amplitude is comparable to the transverse one for most arrangements and usually accompanies irregular cylinder trajectories. Extremely slender figure-8 cylinder trajectories usually seen in single-cylinder VIVs exist only for the tandem arrangements. Arranging the trailing cylinder to vibrate near the wake boundary of the leading cylinder enhances the possibility of irregular trajectories and impacts of both cylinders. Impact between cylinders must occur in cases with irregular cylinder trajectories; however, irregular cylinder trajectories could be found in impact-free cases. The stagger angle significantly changes the attribute of the transverse vibration frequency, toward either the single-cylinder VIV frequency or natural structure frequency in still fluid. The major transverse vibration frequency and the natural structure frequency in still fluid are decoupled for all the side-by-side arrangements and some far spaced tandem arrangements and highly correlated for non-tandem and non-side-by-side arrangements. The time-averaged impact frequency increases with decreasing normalized center-to-center spacing for most combinations of stagger angle and reduced velocity. Apart from the side-by-side arrangements, high-frequency impacts occur when the trailing cylinder is initially located in or near the wake zone of the leading cylinder. The mechanism of trailing cylinder chopping the gap-flow vortices plays an important role in determining the near-wake vortex structures for all non-side-by-side arrangements.

1. Introduction

Uniform flow over a cylinder has attracted much interest among researchers. Vortex shedding in the wake of the cylinder frequently occurs and causes periodic forcing to the cylinder. If the cylinder is allowed to vibrate freely in the flow, the vortex shedding and the cylinder motion will influence each other, eventually synchronize and reach a state of balanced vibration, called vortex induced vibration (VIV). When the frequency of the wake vortex mode matches that of the cylinder vibration, the "lock-in" (also called "resonance" or "synchronization") phenomenon occurs. The vibration amplitude is not necessarily large when lock-in occurs. For the sake of brevity, the term "lock-in" in the present study implies the lock-in with large vibration amplitude.

VIV of an isolated circular cylinder, rigid or flexible, has been studied extensively in the literature. The parameters involved are the mass ratio m^* $(= m/m_d)$, damping ratio ζ $(= c/c_{crit,w})$, reduced velocity U^* $(= U/f_{nw}D)$, and Re $(= UD/\nu)$ where $m =$ cylinder mass, $m_d =$ displaced fluid mass, $c =$ structural damping, $c_{crit,w} =$ critical damping in still fluid, $U =$ free-stream velocity, $f_{nw} =$ natural structure frequency in still fluid, $D =$ cylinder diameter, and $\nu =$ kinematic viscosity. Some researchers defined the damping ratio based on the critical damping in vacuum, c_{crit}, and the reduced velocity based on the natural structure frequency in vacuum, f_n. Related studies have been reviewed and discussed by Sarpkaya (2004), Williamson and Govardhan (2004), and Bearman (2011).

Particularly, there have been many publications on VIV of a spring-supported rigid circular cylinder at low mass damping constrained to move transversely. Much progress has been made by Prof. Williamson's group with a series of physical experiments (Khalak and Williamson, 1996; Khalak and Williamson, 1999; Govardhan and Williamson, 2000). They showed that two types of

E-mail addresses: mhsuan@webmail.nkmu.edu.tw, meng.hsuan.chung@gmail.com

http://dx.doi.org/10.1016/j.ijheatfluidflow.2017.01.006

responses exist according to the combined mass-damping parameter, $m^*\zeta$, at moderate Reynolds numbers. For low $m^*\zeta$, the response consists of three branches: initial, upper, and lower. These branches are highly correlated with vortex-shedding modes and vibration amplitudes. Williamson and Govardhan (2008) briefly summarized fundamental results and discoveries related to VIV with very low $m^*\zeta$. For high $m^*\zeta$ or low *Re*, only two response branches, initial and lower, were observed. The maximum amplitude of vibration at low *Re* is approximately 0.55*D* in contrast to 1.1*D* at higher *Re* (Singh and Mittal, 2005; Prasanth and Mittal, 2008).

VIV of multiple objects can be found in many engineering applications such as flow past tube bundles of heat exchanger, riser/submarine pipelines near to each other, bridge cables or electrical transmission lines in wind, high-rise buildings in proximity, and closely spaced chimneys. VIV involving two rigid circular cylinders is the simplest configuration in this area of research. The center-to-center spacing, *R*, is one of additional parameters. Previous related important studies are collected and briefly introduced as below.

Among experimental works, Bokaian and Geeola (1984a, b) studied the transverse VIV of a circular cylinder downstream/upstream of an identical fixed circular cylinder. Depending on R/D and structural damping, the cylinder experienced different modes of vibration, i.e., vortex-resonance and/or galloping. The cylinders' aspect ratio significantly influences the galloping amplitudes. Zdravkovich (1985) studied two-degree-of-freedom (2-dof) VIVs of two circular cylinders in various arrangements for $R/D \geq 1.125$ and particularly large values of m^* of order 10^3. The vortex shedding excited vibrations and fluid-elastic vibrations were observed. For the former, the vibration amplitude of the upstream cylinder is not always larger than that of the downstream one. For the latter, three characteristic responses can be identified based on the growth rate of instability and the predominant direction of vibration. Assi et al. (2006) observed that a circular cylinder, undergoing a transverse VIV behind a fixed cylinder, exhibited interference galloping behavior for $2 \leq R/D \leq 5.6$. Kim et al. (2009) and Alam and Kim (2009) investigated the transverse VIVs of two identical circular cylinders in various arrangements. They identified seven response patterns for $1.1 \leq R/D \leq 4.2$, depending on whether vortex-excited and/or galloping vibrations are generated. Huang and Herfjord (2013) studied 2-dof VIVs of two circular cylinders for $R/D \geq 2$. The downstream cylinder was immersed almost within the wake of the upstream one, experiencing a non-zero time-averaged lift which diminishes as the transverse vibration amplitude increases.

Most numerical works focused on small m^* (order 1) and low *Re* (<1000). Mittal and Kumar (2001) investigated 2-dof VIVs of two far spaced circular cylinders for tandem and staggered arrangements. The upstream cylinder was found to behave like a single cylinder and the downstream one exhibited the wake-induced flutter. Prasanth and Mittal (2009) examined similar problems with $m^* = 10$ and found the lock-in zone is larger than that for an isolated cylinder. For the staggered arrangement, the downstream cylinder followed orbital trajectories at most of the reduced velocities investigated, in contrast to the figure-8 trajectories commonly seen for the tandem arrangement. Borazjani and Sotiropoulos (2009) investigated VIVs of two circular cylinders in tandem in the proximity-wake interference regime ($R/D = 1.5$), and identified the excitation mechanisms as the vortex-shedding one and the gap-flow one. The two-dimensional simulations were justified. Carmo et al. (2011) investigated the transverse VIV of a circular cylinder in tandem downstream of a fixed one for $1.5 \leq R/D \leq 8$. Larger lock-in zones with higher peak vibration amplitudes were found in contrast to the single-cylinder case. Bao et al. (2012) studied 2-dof VIVs of two circular cylinders in tandem with $R/D = 5$. It was found that the in-line response of the downstream cylinder, as compared with the transverse one, is more sensitive to the ratio of the in-line to transverse natural structure frequency. Ding et al. (2013) simulated transverse VIVs of two circular cylinders in tandem with $R/D = 2$ and *Re* up to10^5. Their results agreed largely with previous experimental data showing the initial and upper branches in VIV, transition from VIV to galloping, and galloping. For the VIV, vortex shedding exhibited the typical 2S mode in the initial branch and both 2P + 2S and 2P modes in the upper branch. For the galloping, amplitudes of up to 3.5*D* were reported.

The present numerical study aims at comprehensive understanding of the 2-dof VIV of two closely-spaced low-mass zero-damping equal-sized rigid circular cylinders in various arrangements at a low Reynolds number. Most previous experiments focused on flows at high Reynolds numbers. The problem settings of Kim et al. (2009), Alam and Kim (2009), and Huang and Herfjord (2013), among others, are closest to the present ones. However, the former two studied 1-dof VIV and the third treated cases with $R \geq 2D$. All the previous numerical simulations treated only the tandem arrangement except those in the studies of Mittal and Kumar (2001) and Prasanth and Mittal (2009) in which the same and only one staggered arrangement was examined. It was demonstrated that the results of 2-dof VIV are distinctively different from those of 1-dof VIV in terms of the hydrodynamic force and cylinder displacement as a function of reduced velocity for small center-to-center spacings (Borazjani and Sotiropoulos, 2009). We also considered and simulated possible impact of cylinders to clarify its effect on the cylinder response. In contrast to earlier works, the present study features small spacings, diversity of arrangements, and low Reynolds number. The target problem can serve as an elementary model for tube bundles in small-size heat exchanger, e.g., pin-fin heat sink or shell-and-tube heat exchanger. Other engineering applications include two circular pipes close to each other in slurry flows and flow sensor tubing in small systems. Engineering significance can be recognized if fatigue or impact damage due to VIV is considered.

2. Methodology

2.1. Fluid flow solver

For two-dimensional unsteady laminar flows of incompressible fluid, the governing equations consist of the continuity and the Navier–Stokes equations. Being made dimensionless using the cylinder diameter *D* and the free-stream velocity *U* as the characteristic length and velocity respectively, these equations, in the integral form, can be written as

$$\oint_{cs} \mathbf{u} \cdot \mathbf{n} ds = 0 \tag{1}$$

$$\frac{\partial}{\partial t} \int_{cv} \mathbf{u} \, dV + \oint_{cs} \mathbf{u} \, (\mathbf{u} \cdot \mathbf{n}) \, dS = - \oint_{cs} p \, \mathbf{n} \, dS + \frac{1}{\mathrm{Re}} \oint_{cs} \nabla \mathbf{u} \cdot \mathbf{n} \, dS \tag{2}$$

where $\mathbf{u} = u \ \mathbf{i} + \ v \ \mathbf{j}$ represents the fluid velocity vector, and p the pressure normalized by ρU^2 with ρ the fluid density. cv and cs denote the control volume and control surface, respectively, and $\mathbf{n}$ is the outward unit vector normal to the control surface.

Eqs. (1) and (2) constitute a nonlinear and coupled system of partial differential equations and were solved by the adaptive Cartesian cut-cell method (Chung, 2015) which is briefly introduced as follows. The governing equations are discretized on a cell-centered collocated finite volume fixed Cartesian grid. A strategy of Adaptive Mesh Refinement (AMR) is employed such that finer meshes would be deployed in regions with larger velocity gradient or velocity-gradient difference between the adjacent different refinement levels. In contrast to the vorticity controlled strategy (Chung, 2008), the present one generates a little more meshes