Applied Ocean Research 53 (2015) 155–160

Contents lists available at ScienceDirect

Applied Ocean Research

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

Technical Note

The validity of the independence principle applied to the vortex-induced vibration of an inclined cylinder in steady flow

Ming Zhao [a,b,*]

[a] School of Computing, Engineering and Mathematics, Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia
[b] Institute for Infrastructure Engineering, Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia

ARTICLE INFO

Article history:
Received 17 June 2015
Received in revised form 27 August 2015
Accepted 28 August 2015
Available online 16 September 2015

Keywords:
Vortex-induced vibration
Navier–Stokes equations
Numerical method

ABSTRACT

The validity of the independence principle applied to the vortex-induced vibration (VIV) of an inclined cylinder in steady flow is investigated by conducting numerical simulations. In order to create a perfect end-effect-free condition, periodic boundary condition is applied on the two end boundaries that are perpendicular to the cylinder. It is found that the response amplitude and frequency for an inclination angle of $\alpha = 45^\circ$ agree well with their counterparts for $\alpha = 0^\circ$. The numerical results demonstrated the validity of the independence principle in the case of vortex-induced vibration, which has not been demonstrated by laboratory tests due to the difficulty in avoiding the end effects.

1. Introduction

Vortex-induced vibration (VIV) of circular cylinders has been studied extensively due to its engineering significance. The review of the studies on VIV can be found in [1–5]. Baratchi et al. [6] investigated the VIV of a heated cylinder in fluid flow and van Brummlen [7] studied the effects of the added mass on the fluid-structure interaction. Efforts have also been made to control the VIV [8,9]. Compared with the studies where the flow direction was perpendicular to the cylinder, the studies on the VIV of an inclined cylinder are much fewer. For flow past an inclined stationary cylinder, it is commonly believed that the independence principle (IP) is valid for inclination angles up to 45° [10–12]. The inclination angle of 0° corresponds to the case where the cylinder is perpendicular to the cylinder. The IP states that the drag and lift coefficients on the cylinder are independent on the inclination angle if they are normalized by the velocity component perpendicular to the cylinder. It was found that the error of the independence principle increases with increasing inclination angle [11]. By numerical simulations, Lucor and Karniadakis [13] found that the angles of the vortices in the wake are somewhat less than the cylinder's inclination angle for large inclination angles of 60° and 70°.

Some experimental studies were conducted to testify the validity of the IP on the response amplitude and frequency of an elastically mounted inclined cylinder in fluid flow [14–16]. The set up of these experimental studies are shown in Fig. 1(a), where an inclined cylinder is partially submerged in the water flow. The inclination angle α is negative and positive if the submerged part of the cylinder is inclined towards upstream and downstream directions, respectively. The response for a negative inclination angle was found not the same as that for a same positive angle in these experimental studies. The effects of the free-end of the cylinder are to blame for the difference [14]. Vlachos and Telionis [17] found that the free-surface affects vortex shedding almost two to three cylinder diameters below the free surface if an inclined cylinder pierce the free-surface. It appears that it is difficult to obtain ideally end-effect-free results using the laboratory setup shown in Fig. 1(a).

Three-dimensional numerical studies have been conducted to investigate VIV of a cylinder in fluid flow whose direction is perpendicular to the cylinder span [18–20]. van Brummenlen et al. [21] conducted a detailed study on boundary-coupled problems in fluid-structure interaction. In this paper, a numerical study is conducted to study the VIV of an elastically mounted inclined cylinder in a fluid flow. In order to testify the validity of the IP for the vibration amplitude and frequency without the influence from the end effects, the periodic boundary conditions are used at the two end boundaries of the computational domain. It is found that the response amplitude and frequency for an inclined cylinder with an inclination angle of 45° agree very well with those for a non-inclined cylinder.

2. Numerical method

Fig. 1(b) is the computational domain for simulating the VIV of an inclined cylinder in a fluid flow. Simulations are conducted for

* Correspondence to: School of Computing, Engineering and Mathematics, Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia. Tel.: +61 247360085.
E-mail address: m.zhao@westernsydney.edu.au

0141-1187/$ – see front matter © 2015 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apor.2015.08.005

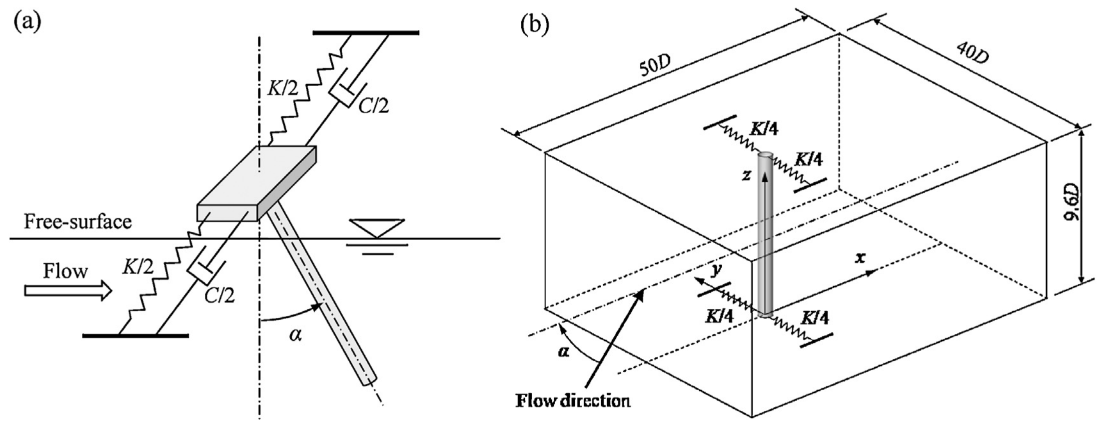

Fig. 1. (a) The computational domain used in this study; (b) the experimental set-up in Franzini et al. [14,15] and Jain et al. [16].

a constant mass ratio of 2, a constant Reynolds number of 1000 and reduced velocities ranging from 2 to 12. The mass ratio, m^*, is defined as the ratio of the cylinder mass to the displaced fluid mass; the Reynolds number is defined as $\mathrm{Re} = U_nD/\nu$, with U_n, D and ν being the velocity component perpendicular to the cylinder, the diameter of the cylinder and the kinematic viscosity of the cylinder, respectively, and the reduced velocity is also defined based on the velocity perpendicular to the cylinder as $V_r = U_n/f_nD$, with f_n being the structural natural frequency of the cylinder, i.e., the natural frequency measured in the vacuum. The damping ratio ζ is set at zero in this study. The damping ratio is defined as $\zeta = C/2\sqrt{Km}$, where C is the damping coefficient measured in vacuum, K is the spring constant and m is the mass of the cylinder.

The interaction between the fluid flow and structures at large Reynolds numbers is generally simulated by the turbulence models. The commonly used turbulence models include large eddy simulation (LES), Reynolds-averaged Navier–Stokes (RANS) equation and the recent developed residual-based variational multiscale turbulence modelling (RBVMS) [22,23]. Although turbulence models can simulate the flow at high Reynolds numbers, they generally introduce uncertainty to the numerical model. To avoid any uncertainty, VIV of a cylinder is solved by direct numerical simulation (DNS) in the laminar flow regime with a Reynolds number of 150 and in the turbulent flow regime with a Reynolds number of 1000. The three-dimensional incompressible Navier–Stokes (NS) equations are solved by the finite element method for simulating the flow and the equation of the motion of the cylinder is solved for predicting the vibration of the cylinder. The NS equations are solved using the Arbitrary–Lagrangian–Eulerian (ALE) scheme. In the ALE scheme, the finite element nodes move according to the vibration of the cylinder. The incompressible NS equations in the ALE scheme are written as

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

$$\frac{\partial u_i}{\partial t} + (u_j - \hat{u}_j)\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu\frac{\partial^2 u_i}{\partial x_i^2}, \tag{2}$$

where x_1, x_2 and x_3 represent the coordinates x, y and z, respectively, u_i is the velocity in the x_i-direction, $\hat{u}_i$ is the velocity component of mesh moving in the x_i direction, ρ is the density of the fluid, p is the pressure and t is the time. The NS equations are solved by the Petrov–Galerkin finite element method developed in [11]. The vibration of the cylinder is simulated by solving the equation of the motion:

$$m\ddot{Y} + C\dot{Y} + KY = F_y, \tag{3}$$

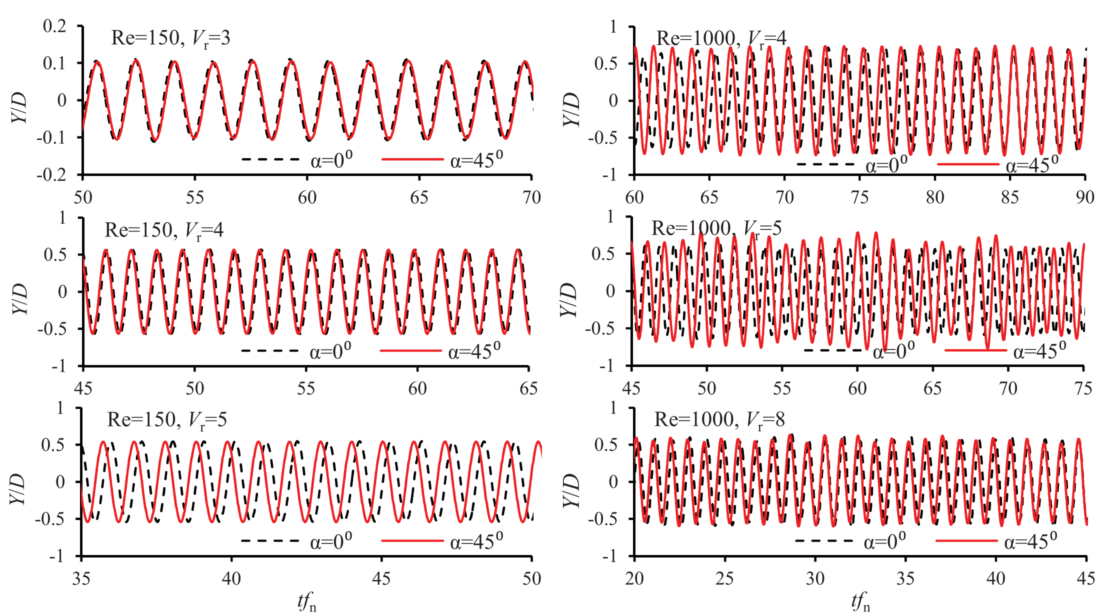

Fig. 2. Time histories of the vibration displacement.