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Direct-forcing immersed boundary modeling of vortex-induced vibration of a circular cylinder

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ABSTRACT

A numerical study of the vortex-induced vibration (VIV) of a flexible supported circular cylinder using the direct-forcing immersed boundary (DFIB) method incorporating the virtual force term is investigated. The use of DFIB method eliminates the requirement of mesh regeneration at each time step, owing to the movement of the cylinder, a practice which is common with body-fitted grid setups. The fluctuating hydrodynamic forces may cause the vibration of the structure due to vortex shedding behind it. In reality, this vibration phenomenon may result in the failure of the structure especially for the so-called lock-in/synchronization phenomenon. The present study shows that a dynamically mounted circular cylinder is allowed to vibrate transversely only or both in the in-line and the transverse directions in a uniform flow at a moderate Reynolds number. The effects of reduced velocity and gap ratio on VIV are discussed. Hydrodynamic coefficients of a freely vibrating cylinder are analyzed in time and spectral domains. The cylinder orbits the slightly oval-shaped and eight-shaped motions in the lock-in regime. Moreover, the 2S and the C(2S) vortex shedding modes can be found at the low amplitude vibration and the large amplitude vibration, respectively. The comparisons against the published data prove the capability of the present DFIB model. This proposed model can be useful for the investigation of VIV of the structures.

1. Introduction

Vortex-induced vibration (VIV) of a structure has become an important issue in many engineering areas, such as aerospace engineering, civil engineering, wind engineering, and ocean engineering. For aerospace engineering, an airfoil subject to the fluttering would be damaged due to the large amplitude vibrations. In the civil engineering and the wind engineering, it may cause galloping of bridges and chimneys due to the interaction with current and wind, respectively. For an offshore application, such as submerged pipelines on a seabed may vibrate acutely due to ocean currents. It results in the damage of flexible risers in petroleum production.

VIV has been regarded as one of the dominating causes for the fatigue failure to the structures. However, this phenomenon could be very useful in renewable energy as well. The kinetic energy of the vibrating structure, which comes from the flow, can be converted to usable electric energy given that a proper power take-off (PTO) mechanism is designed to link the structure and the power generator. Recently, Bernitsas et al. (2008) developed a VIVACE (Vortex-induced vibrations for aquatic clean energy) machine that can harvest energy from most of the water currents around a vibrating structure. Actually, VIV problems are always complicated and exit in situations such as inclined and free shear flows, the effects of turbulence and rigid plane boundary, regular or irregular wave, and so on. To further realize VIV phenomena, the prediction of the amplitude and frequency responses of a vibrating circular cylinder is necessary.

It is well known that VIV exists under the action of unsteady hydrodynamic forces arising from alternative vortex shedding behind a solid body immersed in fluid flow. As vortices shed, the periodic forces exert on the solid body in a flow field. Considering an elastically mounted circular cylinder, the periodic forces lead to the movement of the cylinder. Under certain conditions, the vortex-shedding frequency is close to its natural frequency and then self-excited vibrations would be induced. This phenomenon is referred as lock-in/synchronization which may cause the failure of the structure, especially for the resonance case. The practical significance of VIV has led to a large number of fundamental studies.

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Nomenclature

English Symbols

A	dimensionless amplitude
c	structural damping, N s m^{-1}
d_x, d_y	displacements in the in-line and the transverse directions, m
D	diameter of cylinder, m
$\mathbf{f}^*$	dimensionless virtual force per unit mass
f_n	natural frequency of structure, s^{-1}
f_v	frequency of vortex shedding, s^{-1}
f_n^*	dimensionless natural frequency of structure
f_v^*	dimensionless frequency of vortex shedding
$\mathbf{F}$	total dimensionless virtual force
I, J	numbers of grid points in the x- and y-directions
k	structural stiffness, N m^{-1}
L	axial length of structure, m
m^*	dimensionless mass ratio
m_s	structural mass of solid, kg
p	dimensionless pressure
Re	Reynolds number, $u_\infty D/\nu$
St	Strouhal number, $f_v D/u_\infty$
t	time, s
t^*	dimensionless time
$\mathbf{u}$	dimensionless velocity of fluid
$\mathbf{u}'$	dimensionless first intermediate velocity
$\mathbf{u}''$	dimensionless second intermediate velocity
$\mathbf{u}_s$	dimensionless velocity of solid
u_∞	free stream velocity, m s^{-1}
U_R^*	dimensionless reduced velocity
x, y	horizontal and vertical cartesian coordinates
X, Y	dimensionless displacements in the in-line and the transverse directions

Greek Symbols

η	dimensionless fraction of volume cells
ν	kinematic viscosity of fluid, m^2 s^{-1}
ρ	density, kg m^{-3}
ζ	dimensionless damping ratio of structure
$\mathcal{D}$	convergence criterion

Subscripts

f	fluid
s	solid

Superscripts

n	time step level
$*$	dimensionless parameter
$'$	first intermediate time step level
$''$	second intermediate time step level

Many of them are discussed in comprehensive reviews of the investigations on various aspects of VIV such as Sarpkaya (1979), Bearman (1984), Parkinson (1989) and Williamson and Govardhan (2004). Some literatures claim that a combined mass-damping parameter ($m^*\zeta$) controls the cylinder responses of the VIV system. Herein, m^* is the ratio of the structure mass to fluid mass and ζ is the structural damping. Feng (1968) conducted a well-known experiment on cross-flow vibration of a flexibly mounted circular cylinder in air flow with high $m^*\zeta$. In his study, it demonstrates a typical lock-in phenomenon and the occurrence of resonance of the cylinder over a range of reduced velocity U_R^*. Two amplitude response branches such as the initial and the lower branches exist given that $m^*\zeta$ is high as explained by Khalak and Williamson (1996) and Govardhan and Williamson (2000). Brika and Laneville (1993) studied cases of aeroelastics for a slender cylinder with low $m^*\zeta$ in a wind tunnel. In terms of their flow visualization results, it turns out that the initial branch of the hysteresis loop is associated with the 2S (two single vortices released per cycle) mode and the lower branch with the 2P (two vortex pairs shed per cycle) mode. The experimental studies involving the transverse vibration of an elastically mounted circular cylinder with extraordinarily low $m^*\zeta$ in a water channel was undertaken by Khalak and Williamson (1996, 1997a,b, 1999).For low $m^*\zeta$, three response modes, initial, upper, and lower modes, were reported. They indicated that the transition between the initial and upper response branches involves a hysteresis. This contrasts with the intermittent switching of modes for the transition between the upper and lower branches. In the upper branch, it is also found that the 2P mode exists but the resonant amplitude is distinctly higher than other two branches. Guilmineau and Queutey (2004) reported numerical simulations for the transverse vibration of a flexibly mounted circular cylinder with low $m^*\zeta$ in turbulent flow. In their study, three initial conditions were considered: rest, increasing velocity, and decreasing velocity. It is showed that the simulations predict only the lower branch under rest and decreasing velocity. On the other hand, with the increasing velocity condition, the upper branch is predicted. Blevins and Coughran (2009) conducted experimental investigations in one and two dimensional VIV of an aeroelastic circular cylinder with various m^* and ζ in turbulent water flow.They pointed out that the in-line frequency is approximately twice the transverse frequency and the two-degree-of-freedom cylinder orbits an eight-shaped motion.

The advantages for predicting physical phenomena in advance and reducing the cost have been generally accepted in computational fluid dynamics (CFD). The immersed boundary (IB) method is a novel numerical methodology for the simulation of fluid–structure interaction problems due to its capability to handle simulations for a moving boundary with less computational cost and memory requirements than the conventional body-fitted method since it was introduced by Peskin (1972). The IB method includes a virtual force in the Navier–Stokes equations to express the effect of fluid–structure interaction. An alternative IB method named the direct-forcing method was introduced by Mohd. Yusof (1996). Instead of using a velocity interpolation to distribute the force from a Lagrangian grid to an Eulerian grid, Noor et al. (2009) used the so-called volume of solid function to link the force in the fluid–structure interaction. It does not require re-meshing for moving body problems at each time step since it uses the Cartesian grids. The idea of the direct-forcing immersed boundary (DFIB) method has been adopted and obtained successful applications. Wang et al. (2008) conducted a multi-DFIB method for the modeling of the hitting and rebounding process of the single particle sedimentation and the sedimentation of multi-particles. Their quantitative comparisons against other studies of the flows laden with moving particles validated their model. Luo et al. (2012) developed a hybrid formulation using an IB method which represents for the association between the solid body surface and the local flow reconstruction to the validations including two- and three-dimensional, stationary, and moving boundaries. This approach can suppress the force oscillations and computational cost for the numerical