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Numerical study on vortex-induced vibration responses of a circular cylinder attached by a free-to-rotate dartlike overlay

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ABSTRACT

In the present paper, the two-degree-of-freedom vibration responses of a circular cylinder attached by a free-to-rotate dartlike overlay with Reynolds number ranging from 1715.9 to 6851.6 are modeled in two dimensions by using the commercial CFD code "Fluent". The rotation of the dartlike overlay can disturb the flow around the cylinder and simultaneously convert hydrokinetic energy to mechanical energy. The URANS equations and SST k-ω turbulence model are employed to calculate the flow field, while a fourth-order Runge–Kutta method is applied to evaluate the motion of the system. It is found that the overlay rotates counterclockwise under the drive of fluid flow, resulting in 2S wake mode throughout the reduced velocity range. The boundary layer separation points move to the four tips of the overlay. Due to the shearing action of rotating overlay, small vortices are cut off from the vortices shedding from overlay tips. The rotation of overlay speeds up the migration of the vortices to the downstream. However, as the reduced velocity is larger than 6.7, the vibration of the system is enhanced. So this free-to-rate overlay can be used as power generation device at high reduced velocity.

1. Introduction

Flow over a circular cylinder leads to separation of boundary layer and alternating vortices shed in the wake region. Circular cylinders experience vortex-induced vibration (VIV) as a result of the periodic vortex shedding over a wide range of *Re*. This phenomenon is common in many engineering problems such as flow past a bridge support, a chimney, a heat exchanger tube, a submarine pipe, an offshore riser, etc. When the frequency of the vortex shedding corresponds to one of the structure's resonant frequencies, the cylinder would be excited to undesired strong vibrations. This kind of vibrations may cause fatigue damage in the structures. So VIV is usually treated as a destructive phenomenon and a large number of methods have been proposed to suppress VIV responses. Geometric modification of cylinder wall or attaching additive devices to the cylinder is a conventional method to disturb the separation of boundary layer, which is called as passive control method. Typical examples are helical strakes (Zhou et al., 2011; Lee et al., 2014), splitter plates (Hwang et al., 2003; Sudhakar and Vengadesan, 2012; Gu et al., 2012), fairings (Eisenlohr and Eckelmann, 1989; Khorasanchi and Huang, 2014) and small control cylinders (Dalton et al., 2001; Zhao et al., 2005, 2007; Zhu and Yao, 2015). Another method, named as active control method, achieves the VIV suppression purpose by input external energy. Some illustrative examples can be considered as rotating cylinders at a certain speed (Dennis et al., 2000; Choi et al., 2002), oscillating cylinders at an appropriate frequency (Cetiner and Rockwell, 2001; Carberry et al., 2003; Lee and Lee, 2008), steady or time-periodic blowing and suction (Yao and Sandham, 2002; Fujisawa et al., 2004), electromagnetic forcing (Kim and Lee, 2000) and distributed forcing controls (Kim and Choi, 2005).

In various engineering applications, VIV suppression is highly significant. However, vortex-induced vibration is a double-edged sword. This potentially disastrous phenomenon can be utilized to generate power with VIVACE (Vortex-induced vibration for aquatic clean energy) converter (Bernitsas and Raghavan, 2009). This VIVACE converter is invented by Bernitsas and Raghavan in 2005 to harvest energy from vortex-induced vibration and further developed by the marine renewable energy laboratory at the University of Michigan (Bernitsas et al., 2009; Lee and Bernitsas, 2011; Raghavan and Bernitsas, 2011; Ding et al., 2013). From this point of view, enhancing the oscillation amplitude of cylinder is favorable.

In this paper, a dartlike overlay covering over a circular cylinder is proposed to examine the effect on VIV response. This dartlike overlay replacing the circular cylinder is subjected to uniform flow. Under the impact of flow, the dartlike overlay is free to rotate, which can disturb the flow around the cylinder and at the same time convert hydrokinetic energy to mechanical energy. The goal of this work is to investigate the effect of flow velocity on the VIV

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response of a circular cylinder attached by a free-to-rotate dartlike overlay. The 2D URANS (unsteady Reynolds- Averaged-Navier-Stokes) approach and SST (shear stress transport) k-ω turbulence model are employed to capture flow properities. A fourth-order Runge–Kutta method is applied to evaluate the 2-DOF (two-degree-of-freedom) vibration of the system.

2. Problem description

Fig. 1 shows the cylinder with a free-to-rotate dartlike overlay supported by the spring and damper in a uniform flow. The diameter of cylinder D is 38.1 mm. And the cylinder is enclosed by a dartlike overlay with the overlay internal surface tangent to the cylinder wall. The four same sides of the dartlike overlay are connected end-to-end. And each side contains a straight line and a one-fourth arc. The length of the straight line (L) and the diameter of the arc ($2R$) are both equal to the cylinder diameter.

This system can vibrate in the in-line (IL) and cross-flow (CF) directions. The mass ratio of the circular cylinder is $m^*=2.4$ ($m^*=4\,m/\rho\pi D^2$, where m is the mass of the cylinder per unit length, $m=\rho_c\pi D^2/4$, ρ_c and ρ are the densities of the cylinder and the fluid, respectively, i.e., $\rho_c/\rho=2.4$). The dartlike overlay is made out of the same material as the cylinder, so the mass ratio of the whole system is $m^{*'}=(m+m_o)/(m_w+m_{ow})$, where m_o is the mass of the overlay per unit length, $m_o=\rho_c A$, A is the cross-sectional area of the overlay, m_w is the displaced mass of fluid due to the cylinder, $m_w=\rho\pi D^2/4$, m_{ow} is the displaced mass of fluid due to the overlay, $m_{ow}=\rho A$. Therefore, the mass ratio is also 2.4 for the system ($m^{*'}=\left[\rho_c(\pi D^2/4)+\rho_c A\right]/\left[\rho(\pi D^2/4)+\rho A\right]=\rho_c/\rho$). The stiffness and structural damping ratio of the system are kept at $k=17.26$ N/m and $\zeta=5.42\times10^{-3}$, respectively. The reduced velocity is defined as $U_r=u_{in}/f_n D$, where u_{in} is free-stream rate and f_n is the natural frequency in vacuum ($f_n=0.4$, which can be calculated by $\sqrt{k/m}/2\pi$). In simulations, the reduced velocity is changed from 2.95 to 11.80, corresponding to Re ranging from 1715.9 to 6851.6. Ten different reduced velocities are considered to examine the effect of flow velocity on the VIV response.

As shown in Fig. 1, the computational domain is a rectangle region, and the overall is 30D in the streamwise direction and 16D along the cross-flow direction. The center of the cylinder is 8D from the inlet boundary. And the lateral boundaries are set at 8D from the centerline. An accompanying moving zone around the oscillator with diameter of 2.6D is defined, which has the same translational motion as the cylinder in order to improve the mesh updating efficiency. The dynamic zone around the accompanying moving zone is a square 10D on a side. The mesh in the dynamic zone can deform and perform any needed adaptation based on the motion of the oscillator and accompanying moving zone. The rest is static zone, in which mesh is unchanged in the simulation process.

The boundary conditions are also shown in Fig. 1. The no-slip boundary condition is assigned on the surfaces of the dartlike overlay. The inflow boundary condition is $u=u_{in}$ and $v=0$, at $x/D=-8$ for $-8\le y/D\le 8$. And the outlet boundary condition is $\partial u/\partial x=0$ and $\partial v/\partial x=0$, at $x/D=22$ for $-8\le y/D\le 8$. The two lateral boundaries are defined as slip boundary condition with $\partial u/\partial y=0$ and $v=0$.

3. Mathematical model and numerical approach

3.1. Governing equations

For an unsteady, two-dimensional, turbulent and incompressible fluid flow, the URANS equations can be employed to capture flow properties past the circular cylinder with a free-to-rotate dartlike overlay, including continuity and momentum equations expressed as:

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

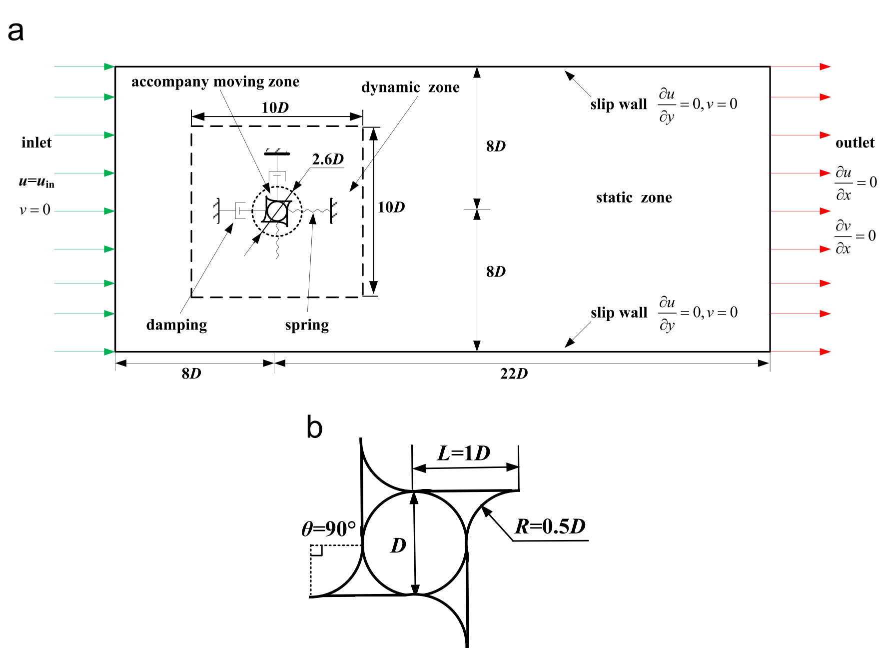

Fig. 1. Sketch and definition of fluid flow past a circular cylinder with dartlike overlay: (a) computational domain and boundary conditions; (b) set-up of a circular cylinder with dartlike overlay.