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Numerical simulation of vortex induced vibrations of a flexibly mounted wavy cylinder at subcritical Reynolds number

Kai Zhang[a,b], Hiroshi Katsuchi[b], Dai Zhou[a,c,d,*], Hitoshi Yamada[b], Tao Zhang[b], Zhaolong Han[a,e]

[a] School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Department of Civil Engineering, Graduate School of Urban Innovation, Yokohama National University, Yokohama 2408501, Japan
[c] Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration (CISSE), Shanghai 200240, China
[d] State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, No. 800, Dongchuan Road, Shanghai 200240, China
[e] Cullen College of Engineering, University of Houston, Houston, TX 77004, USA

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ABSTRACT

Wavy cylinders have been proven effective in controlling the flow and reducing the fluid induced forces. However, the hydro-elastic behavior of a flexibly mounted wavy cylinder remains unclear. The current paper endeavours to present a systematic study of the flow around a spring mounted wavy cylinder mainly at a moderate Reynolds number of 5000, the results of which are compared with a normal cylinder with the same fluid and structural attributions. It is discovered that the wavy cylinder, although almost eliminates the Kármán vortices in the fixed configuration, shows only limited efficacy on the mitigation of the flow induced vibration in the case of zero structural damping, and the typical initial-upper-lower type response curve is manifested. The hydrodynamic forces of the wavy cylinder also magnify significantly in the flexibly mounted cases during synchronization. Moreover, the phase lag between the lift coefficient and the displacement displays a clear change from 0° at the initial branch to 180° at the lower branch. The association of the 2*S* and 2*P* vortex shedding modes to the different branches is also similar to that of the normal cylinder, in which the 2*S* mode corresponds to the initial branch and the 2*P* to the lower branch. In general, despite the absence of the primary shedding frequency in the fixed configuration, the flexibly mounted wavy cylinder exhibits many features that is also found in the normal cylinder. This implies that the vortex induced vibration may not be initiated by the Kármán vortex shedding, and thus may defy the conventional view on the mechanism of the vortex induced vibrations. Additional simulations are performed with non-zero structural damping. It is disclosed that with sufficiently high structural damping, the vibration of the wavy cylinder could be reduced more efficiently than the normal cylinder.

1. Introduction

Circular cylindrical structures are widely used in engineering applications such as deepwater risers, free spanning pipelines, overhead transmission lines, bridge stay cables, etc. Being long and flexible, these structures are plagued by the excessive fluid forces as well as the ensuing vortex induced vibrations (VIV), which increases the construction cost and undermines the fatigue life. Aiming at alleviating these problems, considerable efforts have been dedicated to the manipulation of the flow behind a circular cylinder (Kumar et al., 2008). Among them, span-wise modification near the separation point, referred to as 3D forcing by Choi et al. (2008), has been recognized as an effective control method for the reduction of hydrodynamic forces on a circular cylinder. Typical examples of this category include sinus axis and helical bumps (Owen et al., 2001), small size tabs (Yoon, 2005), span-wise blowing and sucking (Kim and Choi, 2005), etc.

Another particular form of 3D forcing that has recently drawn the attention of several researchers is the span-wise waviness, i.e., straight axis with sinusoidally varying diameter. Ahmed and Bays-Muchmore (1992) and Ahmed et al. (1993) were among the first the have experimentally studied this kind of structures. Lam and his colleagues have also been active in this field. They conducted a series of systematic investigations focusing on the flow physics and the shape optimizations of the sinusoidal wavy cylinder, with Reynolds number spanning from 100 to 50,000 (Lam et al., 2004, 2004; Lam and Lin, 2008, 2009). Xu et al. (2010) numerically examined the compressible flow past a wavy cylinder. Lee and Nguyen (2007) and Zhang and Lee (2005) both employed flow visualization techniques to study the wavy cylinder

* Corresponding author at: School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China.
E-mail address: zhoudai@sjtu.edu.cn (D. Zhou).

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wakes. Based on these works, some salient features of this particular shape could be summarized here. (i) The wavy geometry enforces span-wise non-uniformity in the separation angle. The free shear layers emanating from the undulated separation line are contorted in a 3 dimensional fashion. (ii) The 3D free shear layers are more resistant to rolling-up, thus the Kármán vortices are suppressed and develop further downstream. (iii) The drag and lift forces, owing to the elongated vortex formation length, are significantly mitigated. The stabilizing effect of the artificially generated span-wise waviness on an otherwise two dimensional wake base flow is further justified from the perspective of stability analysis by Hwang et al. (2013). Based on the above experimental, numerical and theoretical investigations, it could be concluded that the span-wise waviness presents a promising morphology if one is seeking for the mitigation of fluid induced forces.

The previous researchers have mainly focused on the forces and wakes of the fixed wavy circular cylinders, coming to the conclusion that this very shape could suppress the Kármán vortex shedding and reduce the drag and lift forces. An implicit conclusion has been inferred that VIV could also be mitigated if the wavy cylinders are elastically mounted. However, based on Owen et al. (2001)'s research on flow past cylinders with sinus axis and helical bumps, in which vortex induced vibrations was not eliminated even though vortex shedding was totally suppressed for the same fixed body, Dong et al. (2008) pointed out that some of the flow control techniques may be effective only for the stationary cylinders rather than flexibly mounted ones. Another example attesting to this statement is provided by Pastó (2008). He incorporated the effect of surface roughness and flow turbulence into an effective Reynolds number Re_{eff} and found out that the cylinder might experience VIV even in the critical Re_{eff} regimes in which coherent vortex shedding ceases to persist in the steady configuration. Extending our discussion a little wider to bridge models, El-Gammal et al. (2007) revealed that when attaching a span-wise sinusoidal perturbation module (SSPM) to a plate girder bridge model, considerable discrepancy could be noted in the flexibly mounted case and the fixed case: SSPM is effective in the former while ineffective in the latter. The anticipation that the wavy cylinders are capable of mitigating VIV is confounded by these conflictive statements. A detailed investigation on the response of the flexibly mounted wavy cylinders is in need to demystify this issue.

Vortex induced vibrations of circular cylinders involve quite a number of factors such as mass ratio, damping, stiffness, Reynolds number, incoming turbulence intensity, etc., the study of which has fostered voluminous publications that are based on various methods. Comprehensive reviews on these subjects could be found in Sarpkaya (2004), Gabbai and Benaroya (2005), Williamson and Govardhan (2008) and so on. The VIV phenomenon is generally recognized as a resonance effect with nonlinear feedback (De Langre, 2006). It is featured by self-excited and self-limited oscillations over a range of reduced velocities in which the vibration frequency locks itself to the natural frequency of the system. The variation of maximum vibration amplitude with respect to reduced velocity could be fit into Feng's two branch (initial-lower) curve (Feng, 1968), typical for larger mass ratio and damping, or three branch (initial-upper-lower) curve of Khalak and Williamson (1999) for lower mass-damping. Further more, Govardhan and Williamson (2000, 2002) identified a critical mass ratio of around 0.54, below which the vortex induced vibration might occur for all the reduced velocities larger than 5. If the cylinder is allowed to vibrate in both the transverse and in-line directions, the “supper-upper” branch, characterized by massive amplitude of 3 diameters peak-to-peak, is discovered by Jauvtis and Williamson (2004). These findings have important indications on the practical applications, especially the ocean engineering for which the mass ratio of the structure is usually small.

Owing to the advent of high performance digital computers and the development of sophisticated numerical techniques, the recent widespread use of Computational Fluid Dynamics (CFD) has greatly availed the research of VIV and consolidated the understanding of its mechanisms. The vast majority of the computational work on VIV has been done in the laminar regime (Han et al., 2014, 2015; He, 2015b, 2015c, 2015d) as it is free of the turbulence effects, and more importantly, less resource consuming. Higher Re generally encourages larger vibration amplitude, more complicated flow patterns and more elusive forces. The numerical prediction of vortex induced vibrations at moderate Reynolds numbers also presents a challenging task because of the high computational resources needed to resolve the boundary layer as well as the small scale flow details. A number of 2D numerical investigations in conjunction with either RANS or LES turbulence model have been practiced at sufficiently high Reynolds numbers (Mittal and Kumar, 2001; Guilmineau and Queutey, 2004; Al-Jamal and Dalton, 2004; Pan et al., 2007; Wanderley et al., 2008), with the assumption of full correlation in the span-wise direction. Lately, riding on the crest of the ever-increasing computing power, some 3D studies on VIV of circular cylinders at turbulent regimes have emerged (Evangelinos and Karniadakis, 1999; Lucor et al., 2005; Kondo, 2012; Mittal et al., 2013; Jus et al., 2014; Lee et al., 2014; Zhao et al., 2014). These studies have been successful in retrieving useful insights in many aspects associated with the VIV problems.

Following these works, the current paper endeavors to investigate the vortex induced vibration of a wavy cylinder, which, to the authors' knowledge, has not been studied in literature. The aim is to verify whether this particular geometry could reduce the vortex induced vibrations. A wavy cylinder with mass ratio of $m^* = 2.55$ is investigated mainly at Re=5000. It is anticipated that this work would bring about deep insights into the hydro-elasticity of the wavy cylinders. The rest of the paper is organized as follows. Section 2 covers the numerical aspects in the current work. In Section 3 we will present the details of the case set-up, followed by a mesh dependency test in Section 4. In Section 5 we present and the discuss the results. The last section concludes this paper.

2. Governing equations

The Navier–Stokes equations are spatially filtered to yield the governing equations of Large Eddy Simulation (LES), which, in the Arbitrary–Lagrangian–Eulerian (ALE) frame, read as follows:

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial \overline{u}_i}{\partial t} + (\overline{u}_j - \tilde{u}_j)\frac{\partial \overline{u}_i}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) + \tau_{ij}\right], \tag{2}$$

where $(x_1, x_2, x_3) = (x, y, z)$ are the Cartesian coordinates, $\overline{u}_i$ is the filtered velocity tensor and $\overline{p}$ is the filtered pressure, in which the constant fluid density ρ has been incorporated. $\tilde{u}_i$ is the velocity component of mesh moving in the x_i-direction. $\tau_{ij} = \overline{u_i u_j} - \overline{u}_i\overline{u}_j$ is the sub-grid scale (SGS) stress that requires extra modeling. The SGS stress is expressed in a wavy reminiscent of the Boussinesq hypothesis with the introduction of a turbulent eddy viscosity ν_t:

$$\tau_{ij} - \frac{2}{3}k_t\delta_{ij} = -2\nu_t\overline{S}_{ij}, \tag{3}$$

in which $k_t = \tau_{kk}/2$ is the SGS turbulent kinetic energy and $\overline{S}_{ij} = \frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right)$ is the strain rate tensor calculated directly from the resolved scales. In the current paper, the dynamic k-equation model is adopted to solve for the k_t and ν_t, i.e.,

$$\frac{\partial k_t}{\partial t} + \frac{\partial}{\partial x_j}(\overline{u}_j k_t) = P + \frac{\partial}{\partial x_j}\left[(\nu + \nu_t)\frac{\partial k_t}{\partial x_j}\right] - \epsilon,\ P = 2\nu_t\overline{S}_{ij}\overline{S}_{ij},\ \epsilon = C_\epsilon k_t^{1.5}\Delta_{-1}, \tag{4}$$

$$\nu_t = C_k\Delta k_t^{0.5}, \tag{5}$$