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Numerical study of vibrations of a vertical tension riser excited at the top end

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Abstract

This paper presents numerical simulations of vortex-induced vibrations of a vertical riser which is sinusoidally excited at its top end in both one and two directions in still water. A computational fluid dynamics method based on the strip theory is used. The riser's responses to both top-end and two-end excitations are carefully examined. In low reduced velocity cases, the in-line vibrations consist of three components, the low-frequency oscillation, the first-natural-frequency vibration during the riser reversal, and the second-natural-frequency vibration due to vortex shedding. The sheared oscillatory flow along the span causes low-frequency oscillations in higher modes in the in-line direction, thus forming 'X' shaped, 'II' shaped, and 'O' shaped trajectories at various positions along the span when the riser is excited at its top end in one direction. In the presence of excitations in the other direction, more complex trajectories appear.

Keywords: Vortex-induced vibration; Oscillatory flow; Riser; Platform motion; Viv-FOAM-SJTU solver.

1. Introduction

Marine risers can experience vortex-induced vibrations (VIV) when exposed to currents. Furthermore, offshore floating platforms subject to waves, currents or winds may cause risers to reciprocate. Risers are thus exposed to a relatively oscillatory flow with a degree of shear and forced to cross their own wakes, rendering their responses more like wake-induced vibrations. The vortex shedding frequencies keep going up and down due to the continuous flow velocity changes. Lock-in or resonance phenomena occur when the vortex shedding frequencies meet one of risers' natural frequencies.

Vibrations of rigid cylinders in oscillatory flow have been the subject of numerous investigations in the past several decades [1,2]. A comprehensive review of the early investigations can be found in Sumer and Fredsøe [3]. More investigations of vibrations of rigid cylinders in oscillatory flow have been conducted in recent years. Zhao et al. [4,5] conducted two-dimensional numerical studies of vibrations of a circular cylinder in oscillatory flow and combined steady and oscillatory flow. Fernandes et al. [6] experimentally investigated various trajectories of a cylinder in oscillatory flow.

Vortex-induced vibrations of flexible cylinders in oscillatory flow have received more and more attention. Duggal and Niedzwecki [7] conducted a large-scale experimental study of vibrations of a long flexible cylinder in regular waves. Anagnostopoulos and Iliadis [8] used a finite element technique to study the in-line response of a flexible cylinder in oscillatory flow. Park et al. [9,10] and Senga and Koterayama [11] conducted experimental and numerical studies on vibrations of a hanging riser subject to regular or irregular top-end excitations. Riveros et al. [12] experimentally and numerically studied a model riser sinusoidally excited at its top end. More recently, Fu et al. [13] and Wang et al. [14] conducted model tests on vibrations of a flexible cylinder in oscillatory flow. Thorsen at al. [15] improved their semi-empirical method to predict cross-flow VIV of a flexible cylinder in oscillatory flow.

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Most of the previous numerical studies of risers in oscillatory flow are based on semi-empirical methods, and studies based on computational fluid dynamics (CFD) methods are lacking, which can better reveal interactions between the flow and the riser. In the present work, vibrations of a vertical top-tensioned riser sinusoidally excited at its top end are numerically investigated using a CFD method based on strip theory. The simulations are conducted by the in-house solver viv-FOAM-SJTU, which has been validated in previous studies [16,17]. The present article is organized as follows. Key points to be considered in the simulations are introduced at first. Then the capability of the solver to handle the vibrations of flexible cylinders in oscillatory flow is further validated. And simulation results of vibrations of a riser excited at its top end in one and two directions are carefully examined in a later section.

2. Method

The incompressible Reynolds-averaged Navier–Stokes equations are solved numerically to obtain the hydrodynamic forces acting on the riser. The SST $k-\omega$ turbulence model is employed to determine the Reynolds stresses. Considering the large scale in the axial direction of the flow domain, two-dimensional flow strips positioned equidistantly along the span are computed instead of the entire three-dimensional flow field. As Willden and Graham [18] has mentioned, though three-dimensional vortices may develop, an effect of lock-in actually maintains the locally two-dimensional property, making it appropriate to compute the fluid dynamics locally in a two-dimensional way. Hydrodynamic forces at any positions along the span can be interpolated accordingly. The number of simulation strips can be determined by considering the highest mode of vibration. Three strips are required per half wave-length of vibration [18]. The highest mode considered in the present work is the 5th mode. As a result, 20 strips seem sufficient for the simulation. The PIMPLE algorithm in the OpenFOAM is used to compute the two-dimensional flow fields.

In numerical simulations, the top end or two ends of the riser are forced to oscillate sinusoidally. The excitation motion of the riser is a periodic function of time, expressed as

$$x_s = A \cdot \sin\left(2\pi t \cdot T_w^{-1}\right), \tag{1}$$

$$u_s = 2\pi A \cdot T_w^{-1} \cdot \cos\left(2\pi t \cdot T_w^{-1}\right), \tag{2}$$

A being the excitation amplitude, T_w the excitation period, x_s the excitation displacement and u_s the excitation velocity. Reduced velocity U_r and its maximum value $U_{r\ max}$ can be written as

$$U_r = \frac{u_s}{f_{n1} D} = \frac{2\pi A}{T_w f_{n1} D} \cos\left(2\pi t \cdot T_w^{-1}\right) \tag{3}$$

$$U_{r\ max} = \frac{u_{s\ max}}{f_{n1} D} = \frac{2\pi A}{T_w f_{n1} D}, \tag{4}$$

where f_{n1} is the first natural frequency of the riser. In the sinusoidal flow, the Keulegan–Carpenter (KC) number can be expressed as

$$KC = u_{s\ max} T_w \cdot D^{-1} = 2\pi A \cdot D^{-1}, \tag{5}$$

in which $u_{s\ max}$ is the maximum excitation velocity.

Thus, the riser's total displacement x_t at any positions along the span can be expressed in terms of the quasi-static component due to support motion x_s, and the deflections of the riser from its straight-line condition x [19]:

$$x_t = x_s + x. \tag{6}$$

The quasi-static displacement x_s is linear along the span for riser pinned at the two ends. More details about obtaining quasi-static displacements can be found in Clough and Penzien [19]. The equilibrium of forces for this system can be written as

$$f_I + f_D + f_S = f_{Hx}, \tag{7}$$

where f_I, f_D, f_S, f_{Hx} are the inertial, the damping, the spring, and the hydrodynamic forces in the corresponding direction, respectively. The force components can be expressed as $f_I = m\ddot{x}_t$, $f_D = c\dot{x}$, $f_S = kx$, m, c, k being the mass, the damping and the stiffness of the system. Thus we have

$$m\ddot{x}_t + c\dot{x} + kx = f_{Hx}, \tag{8}$$

$$m\ddot{x} + c\dot{x} + kx = f_{Hx} - m\ddot{x}_S. \tag{9}$$

With the riser modeled as a small displacement Bernoulli–Euler bending beam and two ends set as pinned, we have

$$\underbrace{m\frac{\partial^2 x_t(z,t)}{\partial t^2}}_{m\ddot{x}_t} + \underbrace{c\frac{\partial x(z,t)}{\partial t}}_{c\dot{x}} + \underbrace{EI\frac{\partial^4 x(z,t)}{\partial z^4} - \frac{\partial\left[T(z)\frac{\partial x(z,t)}{\partial z}\right]}{\partial z}}_{kx} = f_{Hx}(z,t) \tag{10}$$

$$\underbrace{m\frac{\partial^2 x(z,t)}{\partial t^2}}_{m\ddot{x}} + \underbrace{c\frac{\partial x(z,t)}{\partial t}}_{c\dot{x}} + \underbrace{EI\frac{\partial^4 x(z,t)}{\partial z^4} - \partial\underbrace{\left[T(z)\frac{\partial x(z,t)}{\partial z}\right]}_{\partial z}}_{kx} = f_{Hx}(z,t) - \underbrace{m\frac{\partial^2 x_s(z,t)}{\partial t^2}}_{m\ddot{x}_S} \tag{11}$$

where flexural stiffness EI and linear density m keep constant along the span, while tension $T(z)$ varies along the span due to gravity. This also applies to the cross-flow displacement. In the finite element method, the equations can be discretized as

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{f}_{Hx} - \mathbf{M}\ddot{\mathbf{x}}_S, \tag{12}$$

$$\mathbf{M}\ddot{\mathbf{y}} + \mathbf{C}\dot{\mathbf{y}} + \mathbf{K}\mathbf{y} = \mathbf{f}_{Hy} - \mathbf{M}\ddot{\mathbf{y}}_s, \tag{13}$$

where $\mathbf{x}$, $\mathbf{x_s}$, $\mathbf{y}$, and $\mathbf{y_s}$ are nodal displacement vectors, $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$ are the mass, the damping and the stiffness matrices, and $\mathbf{f}_{Hx}$ and $\mathbf{f}_{Hy}$ are the hydrodynamic force vectors in corresponding directions (including hydrodynamic mass forces). The Rayleigh damping $\mathbf{C} = \alpha\mathbf{M} + \beta\mathbf{K}$ is adopted, where α and β are calculated based on the natural frequencies of two