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Numerical analysis of multi-modal vibrations of a vertical riser in step currents

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ABSTRACT

This paper describes numerical simulations of the vortex-induced vibrations (VIVs) of a long flexible riser in a step current. We consider the model vertical riser tested at the Delta Flume. The simulation is carried out by our in-house computational fluid dynamics (CFD) solver viv-FOAM-SJTU, which was coupled with the strip method and developed in OpenFOAM platform. The vibration modes in both in-line (IL) and cross-flow (CF) directions are accurately predicted. The numerically predicted maximum mean IL displacement and its location differed marginally from the experimental results. The good agreement between the numerical and experimental results proved that this solver was reliable for predicting the VIV response. A large number of numerical tests were then carried out to study the effects of various parameters on VIV responses further. Three main parameters are considered in this study: current velocity, top tension and mass ratio. The intrinsic relationship between the natural frequency and oscillating frequency was analyzed to explain the occurrence of the dominant mode. Based on the numerical results, the regular characteristics of the VIV response with the reduced velocity were pointed out. The curvatures and the maximum mean offset values were proportional to the squares of the reduced velocities.

1. Introduction

Vortex-induced vibration (VIV) is a critical concern for the offshore industry; it affects pipelines, spar platforms and risers. The greatest concern of those is in the field of deep-water oil extraction. Recently, offshore oil platforms have been installed in water depths of over 2000 m. As a result, there is a great need to develop a reliable numerical solver for the prediction of VIV response of risers with very high aspect ratios.

Over the past few decades, VIV responses of long flexible risers have been extensively studied. Model testing has given valuable insights into the phenomenon of VIVs (Chaplin et al., 2005a, 2005b; Huera Huarte, 2006; Huera-Huarte et al., 2006; Huera-Huarte and Bearman, 2009a, 2009b). These model tests have shown that the response included significant contributions from several modes except at the lowest reduced velocities; a temporary mode transition could also occur occasionally. Apart from the experimental studies, numerical investigations have also attracted the attention of researchers. Empirical models and CFD models are the two main numerical methods used to predict the vibrations of risers (Willden and Graham, 2001, 2004, 2006; Srinil, 2010; Duan and Wan, 2016a; Duan et al., 2016). Willden and Graham (2004) investigated the transverse VIVs of a flexible riser with an aspect ratio of the order of 1000. It has been observed that the mode of vibration with frequency closest to the local natural vortex shedding frequency is most likely to be excited. Wang and Xiao (2016) presented a numerical study on VIVs of a vertical riser subject to uniform and linearly sheared currents. The IL and CF vibrations were predicted accurately. Zhang et al. (2017) presented a systematic study of the flow around a spring mounted wavy cylinder mainly at a moderate Reynolds number of 5000. Borazjani and Sotiropoulos (2009) investigated VIVs of two identical 2D elastically mounted cylinders in tandem in the proximity-wake interference regime at $Re = 200$ for systems having one and two degrees of freedom. Zhao and Wan (2016a, 2016b) studied flow past a cylinder and two cylinders by the approaches of SST-DES and SST-DDES.

Chaplin et al. (2005a) compared laboratory measurements of the VIV responses of a riser with the blind predictions obtained via 11 different numerical methods, including six CFD models and five empirical models. It was found that the empirical models were more successful at predicting CF displacements than CFD models. However, the mode transition of the

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Nomenclature

ϕ^m	Modal shape of the *m*th mode
c_x	In-line curvature
c_y	Cross-flow curvature
D	Diameter of the riser
f_n^m	Natural frequency of *m*th mode
f_S	Vortex shedding frequency
f_{ox}	In-line oscillatory frequency
f_{ox}^m	In-line oscillatory frequency of *m*th mode
f_{oy}	Cross-flow oscillatory frequency
f_{oy}^m	Cross-flow oscillatory frequency of *m*th mode
L	Length of the riser
m	Mode number
m^*	Mass ratio
m_x	In-line mode number
m_y	Cross-flow mode number
$\bar{s}$	Time-averaged value of the variable s
σ_s	Standard deviation of the variable s
$s^{\max}$	Maximum value of the variable $s$over elevation z
s_{rms}	Root mean square value of the variable s over elevation z
St	Strouhal number
T_t	Top tension of the riser
u^m	In-line modal weight of *m*th mode
v^m	Cross-flow modal weight of *m*th mode
V_r	Reduced current velocity
x	In-line displacement
y	Cross-flow displacement
z	Elevation

response with respect to time could not be embodied in those empirical models; mode transition is a key feature of VIV responses of long flexible risers. However, the IL responses obtained by the given six CFD models were not in agreement with the experimental results. Thus, there is need for improvement in the accuracy of the CFD model.

The dynamic features of long slender cylinders are determined by many structural parameters. The vibration amplitudes and modes of riser VIV responses are also influenced by the flow field. Using experimental, numerical and empirical models, many researchers have addressed this very important topic. Chaplin et al. (2005b) presented an experimental study of a vertical model riser with a different top tension, which was exposed to a stepped current. In the experiment of Huera-Huarte and Bearman (2009a), three different top tensions were investigated. For the smallest top tension, the initial, lower and upper branches were observed in the dynamic response of the model, whereas for the other top tension cases, the lower branch of the dynamic response vanished. Chen et al. (2012) investigated the dynamic characteristics and VIVs of the deep-water riser with axially varying structural properties. Huang et al. (2011) investigated cases that covered a wide range of riser VIV problems for risers having different outer diameters, lengths, tensioning conditions and current profiles.

For risers having such high aspect ratios and complex flow fields around them, a complete three-dimensional simulation is not feasible. The strip theory is an efficient strategy for solving VIV problems of flexible cylinders with extremely high aspect ratios. Based on the strip theory, we developed the solver viv-FOAM-SJTU by using the open source code package, OpenFOAM. The entire fluid-structure solution procedure was carried out in the time domain via a loose coupling strategy. We applied the mesh movement based on interpolation using the radial basis function (RBF). The solver has good versatility; it allows simulations of VIVs in both CF and IL directions with various aspect ratios, mass ratios, top tensions and current profiles.

To validate the solver, we carried out numerical simulations of the VIVs for the benchmark case. The numerical results were found to be in good agreement with the benchmark data given in Huera-Huarte (2006). Based on the study of the flow field, the intrinsic relationship between the flow field and the vibration response of the riser was analyzed. The main contribution of this paper is that it investigates the parametric effects on the VIV based on the solver viv-FOAM-SJTU. A series of test studies are conducted using different parameters. The effects of top tension, current velocity and mass ratio are investigated, and the response modes and trends analyses under different conditions are presented. The results show multi-mode characteristics of vibrations of the riser.

The rest of the paper is organized as follows. A brief introduction to the numerical methods is given in Section 2. In this section, the governing equations of flow field and structure field are introduced. The detailed algorithm of the fluid-structure interaction strategy is presented. In addition, the post-processing method of displacement responses is presented for modal analyses. In Section 3, the computations are validated by comparison with the benchmark experiment of Huera-Huarte (2006). Section 4 provides a detailed study of the effects of different parameters on VIV. The parameter analysis of the current velocity, the top tension and the mass ratio are investigated separately. In section 5, the study of the VIV responses with respect to the reduced velocity based on the previous results are presented. We analyzed the changes in the standard deviations of the displacement and the curvature as the velocity is reduced. Finally, in the last section, conclusions are drawn based on the results presented.

2. Method

2.1. Flow model

The flow field is modelled by solving the unsteady, incompressible Reynolds-averaged Navier-Stokes (URANS) equations

$$\nabla\cdot\boldsymbol{U}=0 \tag{1a}$$

$$\rho\frac{\partial\boldsymbol{U}}{\partial t}+\rho\nabla\cdot((\boldsymbol{U}-\boldsymbol{U}_g)\boldsymbol{U})-\nabla\cdot(\mu_{eff}\nabla\boldsymbol{U})-(\nabla\boldsymbol{U})\cdot\nabla\mu_{eff}=-\nabla p_{eff} \tag{1b}$$

where $\boldsymbol{U}$ is the flow velocity and $\boldsymbol{U}_g$ is the grid velocity, $\mu_{eff}=\rho(\nu+\nu_t)$ the effective dynamic viscosity, in which ν and ν_t are mixture kinematic viscosity and eddy viscosity, respectively. ν_t is obtained by the SST turbulence model for turbulence closure. $p_{eff}=p+2/3\rho k$ is the effective pressure, in which k is the turbulence kinetic energy.

2.2. Structural dynamic model

A finite element structural model based on the Euler-Bernoulli beam theory is employed to calculate the dynamic response of the cylinder. Supposing that EI and m^* remain constant along the span, we have

$$EI\frac{\partial^4}{\partial z^4}x(z,t)-\frac{\partial}{\partial z}\left[T(z)\frac{\partial x(z,t)}{\partial z}\right]+m\frac{\partial^2 x(z,t)}{\partial t^2}+c\frac{\partial x(z,t)}{\partial t}=f_x(z,t) \tag{3a}$$

$$EI\frac{\partial^4}{\partial z^4}y(z,t)-\frac{\partial}{\partial z}\left[T(z)\frac{\partial y(z,t)}{\partial z}\right]+m\frac{\partial^2 y(z,t)}{\partial t^2}+c\frac{\partial y(z,t)}{\partial t}=f_y(z,t) \tag{3b}$$

The axial force of the pipe $T(z)$ varies spatially, but not temporally, because of the effects of the weights. To solve the structural dynamic equations in Finite Element Methods (FEMs), Eq. (3a) and Eq. (3b) can be