Numerical Study of Riser Vibration Due to Top-End Platform Motions

Bowen Fu*, Di Deng, Decheng Wan‡

State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai 200240, China

*Presenting author: fubowen@outlook.com

‡Corresponding author: dcwan@sjtu.edu.cn

Abstract

The CFD simulations of vortex-induced vibrations of a flexible riser under a swaying and surging platform have been numerically investigated based on the strip theory. The top end of the flexible riser are forced to oscillate in one or two directions. Three cases are considered, one with only one-direction excitation, one with '∞'-shaped excitation trajectory, and one with parabolic excitation trajectory. When the riser was excited in a parabolic trajectory, the vibrations in both directions are enhanced. However, vibrations can be reduced in the '∞'-shaped trajectory case, in which a 'hat'-shaped trajectory has been observed from a reference frame which moves with the straight riser axis.

Keywords: Vortex-induced vibration; top-end platform motion; flexible riser; computational fluid dynamics; fluid-structure interaction; viv-FOAM-SJTU solver

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 in the water. The risers are thus exposed to a relatively oscillatory flow with a degree of shear and forced to cross its own wake, rendering the situation 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 the risers' natural frequencies.

Vortex-induced vibrations of risers subject to waves or top-end excitations have received more and more attention. Duggal et al.[1] conducted a large-scale experimental study of vibrations of a long flexible cylinder in regular waves. Also some researchers [2–4] conducted experimental and numerical studies on vibrations of a hanging riser subject to regular or irregular top-end excitations. Riveros [5] experimentally and numerically studied a model riser sinusoidally excited at its top end.

Most of previous numerical studies of risers subject top-end excitations mainly concentrate on excitations in one direction. However, the top-end platform actually moves in more than one direction, making it necessary for research on two-directional excitations. In the present work, vibrations of a vertical top-tensioned riser sinusoidally excited at its top end in one or two directions 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 [6,7]. The present article is organized as follows. Section 2 introduces the concerned problems, followed by the simulation methods in Section 3 for handling the problems in Section 2. And Section 4 gives the simulation results with detailed analyses. Finally, a curt summary is presented in Section 5.

Problem

To simulate the effect of the top-end platform's motions, the top end of the riser is forced to oscillate in one or two directions. The excitation motion of the riser is a periodic function of time, expressed as

$$x_\mathrm{s} = A \cdot \sin(2\pi t \cdot T_\mathrm{w}^{-1}) \,, \tag{1}$$
$$u_\mathrm{s} = 2\pi A \cdot T_\mathrm{w}^{-1} \cdot \cos(2\pi t \cdot T_\mathrm{w}^{-1}) \,, \tag{2}$$

A being the oscillating amplitude and T_w the oscillating period, x_s the oscillating displacement and u_s the oscillating velocity. The maximum excitation reduced velocity $U_{\mathrm{r\,max}}$ can be written as

$$U_{\mathrm{r\,max}} = \frac{u_{\mathrm{s\,max}}}{f_{\mathrm{n}1} D} = \frac{2\pi A}{T_\mathrm{w} f_{\mathrm{n}1} D} \,, \tag{3}$$

where $f_{\mathrm{n}1}$ is the first natural frequency of the riser. In the sinusoidal flow, the Keulegan-Carpenter (KC) number can be expressed as

$$KC = u_{\mathrm{s\,max}} T_\mathrm{w} \cdot D^{-1} = 2\pi A \cdot D^{-1} \,, \tag{4}$$

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

Table 1: Main structural properties of the flexible riser.

	Symbols	**Values**	**Units**
Mass ratio	m^*	1.53	−
Diameter	D	0.024	m
Length	L	12	m
Bending stiffness	EI	10.5	$\mathrm{N \cdot m^2}$
Top Tension	T_w	500	N
First natural frequency	$f_{\mathrm{n}1}$	1.08	Hz
Second natural frequency	$f_{\mathrm{n}2}$	2.16	Hz
Third natural frequency	$f_{\mathrm{n}3}$	3.25	Hz

Method

In order to compute the vibrations of flexible risers, the hydrodynamic forces acting on them must be obtained. To do this, the transient incompressible Reynolds-averaged Navier–Stokes equations are solved numerically, 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 fields located equidistantly along the span are solved instead of the entire three-dimensional flow field is not quite feasible. In this case, to solve. As Willden and Graham[8] has mentioned, though three-dimensional vortices might be developed when flow past a riser, an effect of lock-in actually maintain the locally two-dimensional property, making it possible for us to compute the fluid dynamics locally in a two-dimensional way. The hydrodynamic forces at other positions along the span can be interpolated accordingly. The PIMPLE algorithm in the OpenFOAM is used to compute the two-dimensional flow fields.

The flexible riser is modeled as a small displacement Bernoulli–Euler bending beam, with two ends set as pinned. In the present work, the top end of the riser oscillates harmonically as prescribed. Thus, the beam's total displacement is referred to as total displacement x_{t}, i.e. the sum of the support motion x_{s}, plus the relative displacement x:

$$x_{\mathrm{t}} = x_{\mathrm{s}} + x. \tag{8}$$

The equilibrium of forces for this system can be written as

$$f_{\mathrm{I}} + f_{\mathrm{D}} + f_{\mathrm{S}} = f_{\mathrm{H}}, \tag{9}$$

where f_{I}, f_{D}, f_{S}, f_{H} are the inertial, the damping, the spring, and the hydrodynamic forces, respectively. The force components can be expressed as $f_{\mathrm{I}} = m\ddot{x}_{\mathrm{t}}$, $f_{\mathrm{D}} = c\dot{x}$, $f_{\mathrm{S}} = kx$, where m, c, k are the mass, the damping and the stiffness of the system. We have

$$m\ddot{x}_{\mathrm{t}} + c\dot{x} + kx = f_{\mathrm{H}}, \tag{10}$$
$$m\ddot{x} + c\dot{x} + kx = f_{\mathrm{H}} - m\ddot{x}_{\mathrm{s}}. \tag{11}$$

Thus there will be one additional contribution to the total forces from the point of view of the riser, the additional inertial force. In the finite element method the equations can be discretized as

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F}_{\mathrm{H}x} - \mathbf{M}\ddot{\mathbf{x}}_{\mathbf{s}}, \tag{12}$$
$$\mathbf{M}\ddot{\mathbf{y}} + \mathbf{C}\dot{\mathbf{y}} + \mathbf{K}\mathbf{y} = \mathbf{F}_{\mathrm{H}y} - \mathbf{M}\ddot{\mathbf{y}}_{\mathbf{s}}, \tag{13}$$

where $\mathbf{x}$, $\mathbf{x}_{\mathbf{s}}$, $\mathbf{y}$, and $\mathbf{y}_{\mathbf{s}}$ are nodal displacement vectors, and $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$ are the mass, the damping and the stiffness matrices. 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 mainly involved modes, with a damping ratio ζ of 0.03. The equation can be written as

$$\begin{bmatrix}\alpha\\ \beta\end{bmatrix} = \frac{2\zeta}{f_{\mathrm{n}i}+f_{\mathrm{n}j}}\begin{bmatrix}2\pi f_{\mathrm{n}i}f_{\mathrm{n}j}\\ 1/(2\pi)\end{bmatrix}. \tag{14}$$

$\mathbf{F}_{\mathrm{H}x}$ and $\mathbf{F}_{\mathrm{H}y}$ are the hydrodynamic force vectors in corresponding directions (including hydrodynamic mass forces). The equations are solved using the Newmark-beta method [9].

At the beginning of each time step the hydrodynamic forces are mapped to the structural model nodes. Then the displacements of the riser are computed. With the displacements obtained, the mesh can be moved or deformed accordingly, thus resulting in new flow fields from which the hydrodynamic forces can be gained. In this way, a time step is advanced. The procedure is shown in Figure 2, based on which the solver viv-FOAM-SJTU is formed. Twenty strips equidistantly located along the span of the riser are plotted in Figure 3. These strips share the same initial flow field mesh, as shown in Figure 4. The motion solver "displacementLaplacian" in OpenFOAM is applied to handle the dynamic mesh [10]. Imposed on the surface of the riser is the no-slip boundary, and no external current is applied. The riser is discretized into 80 elements, with each element imposed of uniformly distributed loads.

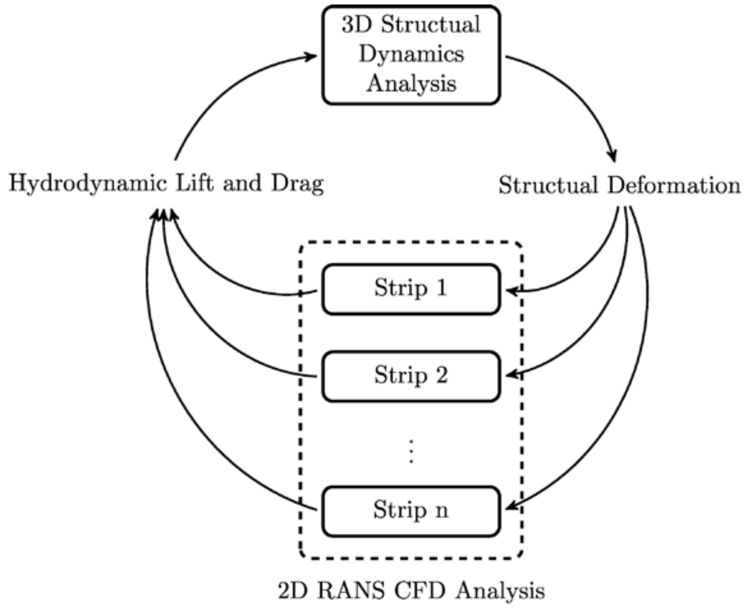

Figure 1: Fluid-structure interaction. The fluid and the structure are coupled by hydrodynamic forces and structural deformations.

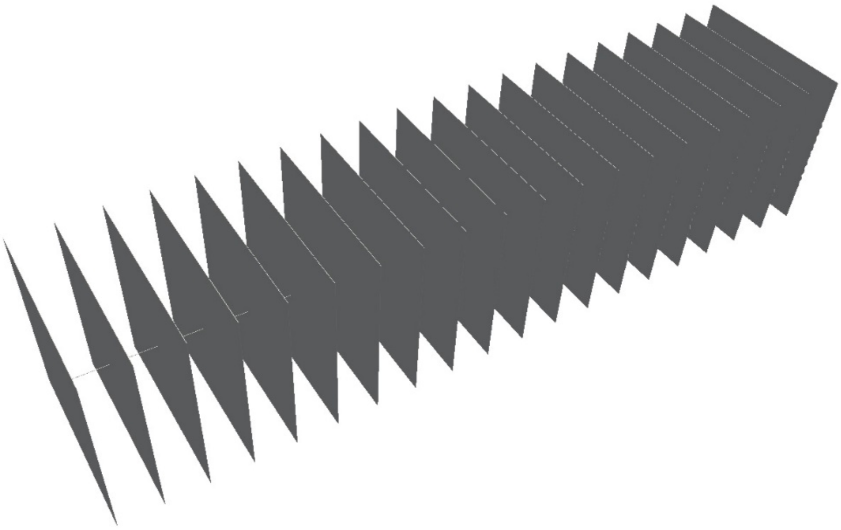

Figure 2: Twenty strips located equidistantly along the span of the flexible riser.

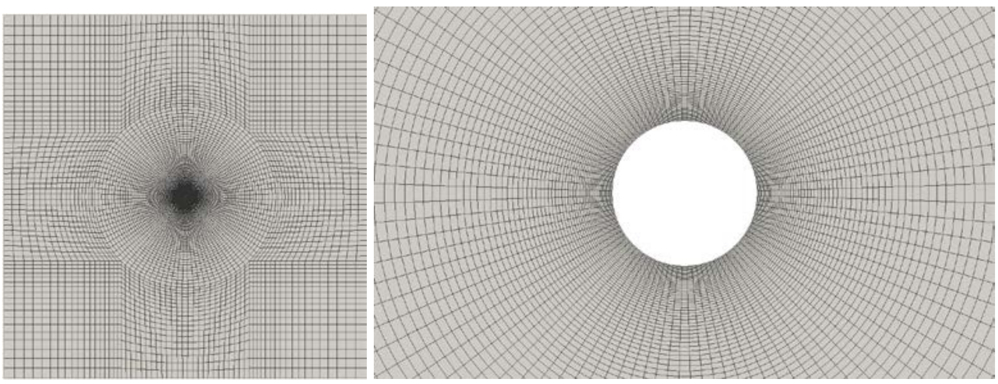

Figure 3: Initial mesh on each strip. The mesh near the riser is magnified. Eighty diameters in the in-line direction x, forty diameters in the cross-flow direction y.

Table 2: Main parameters for simulation cases. Symbols KC_x, KC_y, $U_{\mathrm{r\,max}}$ and $V_{\mathrm{r\,max}}$ denote KC numbers and reduced velocities at the top end of the riser in the in-line and cross-flow directions, ψ being the phase difference between the excitation in two directions.

Case	KC_x	KC_y	$U_{\mathrm{r\,max}}$	$V_{\mathrm{r\,max}}$	ψ
1	84	0	12	0	-
2	84	21	12	6	0
3	84	21	12	6	90

Results

Three cases considered in the present work are listed in Table 2. In Figure 4 are plotted the trajectories of them. When the riser is excited in two directions, the frequency of the cross-flow excitation is set as twice that of the in-line excitation, thus forming '∞'-shaped or parabolic trajectories in Figure 4. An interesting 'hat shaped trajectory (viewed from a reference frame which moves with the straight riser axis) is found in case 2. In case 2, risers move upwards in the cross-flow direction when passing the intersection ('X') parts of the '∞' trajectories. Near the intersections are the high speed periods and consequently large drag forces, causing large deflections in the opposite directions. High speeds also mean more intense vibrations in the locally cross-flow direction, forming the lower 'crab plier' shaped parts. Thus the two 'crab plier'-like parts in Figure 5 correspond to the 'X' parts in Figure 4 while the top-end knots in Figure 5 correspond to two sides in Figure 4, the zero in-line excitation velocity periods. Since at two sides of '∞' the riser is always moving downwards, causing the top-end knots in Figure 5 to move upwards. Though the trajectories in cases 1 and 3 seem similar in Figure 4, i.e. of overlapping forward and backward routes, the curvature actually plays a subtle role in the vibrations, resulting in quite different results in Figs. 5-7. The constantly changing motion directions together with the wake effects render more complex flow situations and also larger deflections in case 3.

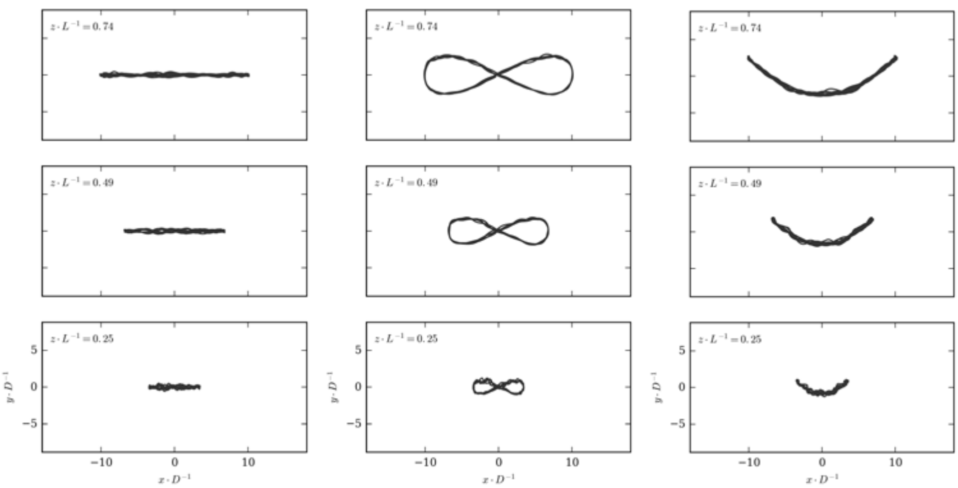

Figure 4: Actual trajectories of the vibrations of the riser in cases 1 (left), 2 (middle), and 3 (right) viewed from a fixed camera.

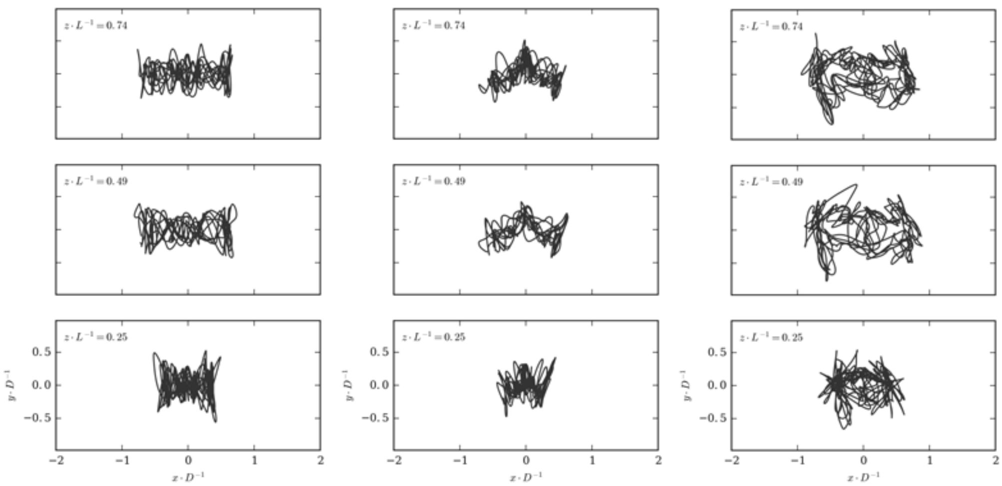

Figure 5: Trajectories of the vibrations of the riser in cases 1 (left), 2 (middle), and 3 (right) viewed from a reference frame which moves with the straight riser axis.

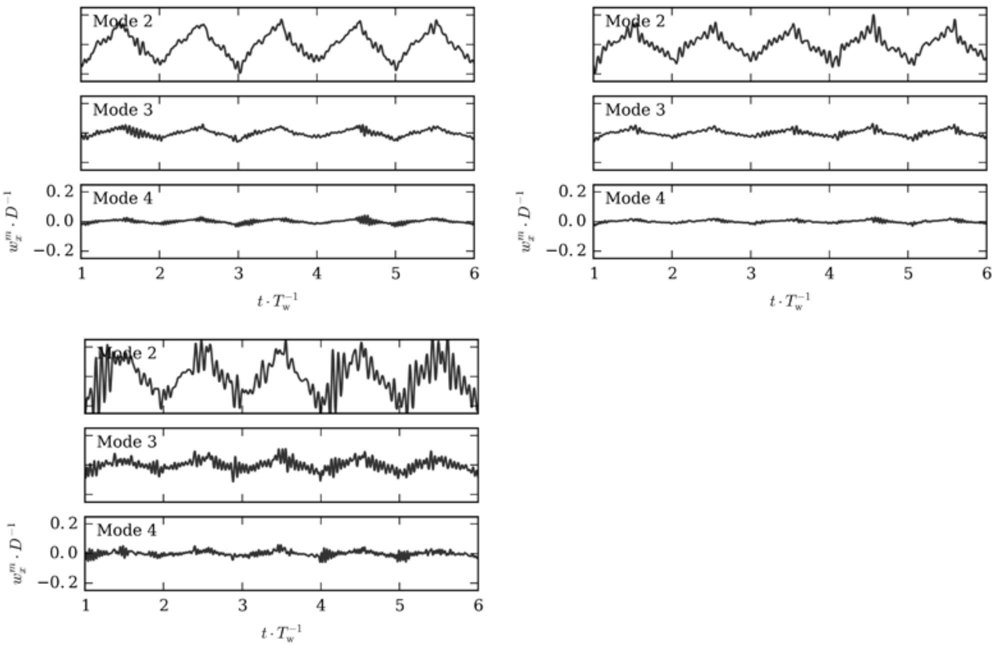

Figure 6: Time series of modal weights of the in-line displacements $x \cdot D^{-1}$ in cases 1 (left), 2 (middle), and 3 (right), $w_x^m \cdot D^{-1}$.

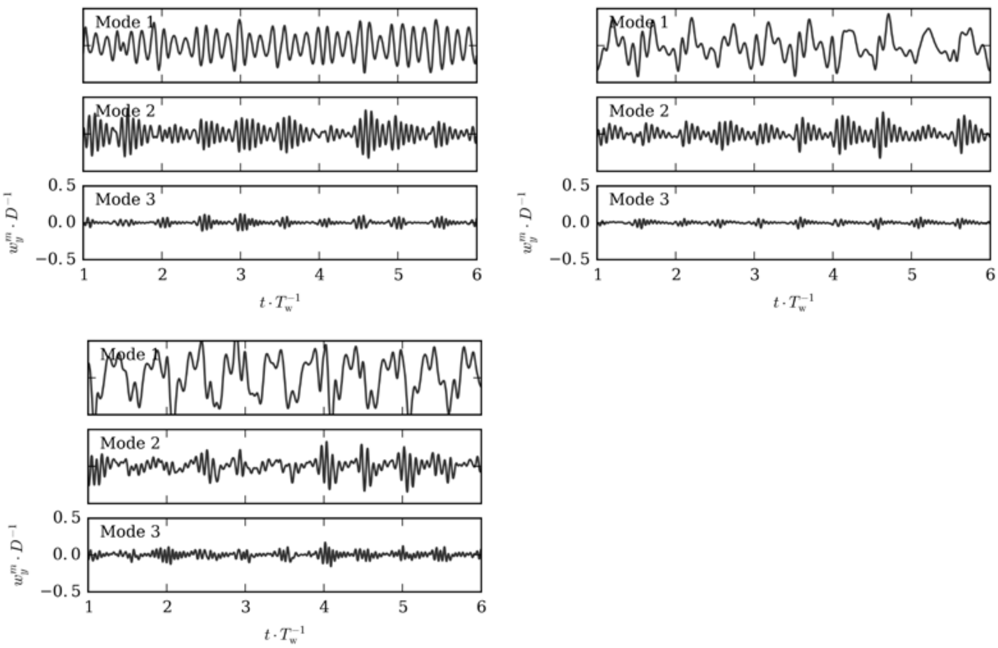

Figure 7: Time series of modal weights of the cross-flow displacements $y \cdot D^{-1}$ in cases 1 (left), 2 (middle), and 3 (right), $w_y^m \cdot D^{-1}$.

Time series of modal weights of the in-line and cross-flow displacements are presented in Figures 6 and 7, respectively. Modal decompositions are conducted in the least-squares sense[11,12]. The low-frequency components due to the current speed variation along the span appear in higher in-line modal weights in all cases. These also occur in the cross-flow direction in case 2 and 3, but the low frequency is twice of the in-line one, the same with the excitation frequency in the corresponding direction. It is clear from Figures 5-7 that the vibrations become more intense in both directions in case 3, especially in the in-line direction, indicating that the excitation in the other direction can enhance the vibrations when the riser has to cross its own wake. The pretty intense second modal weight of in-line displacement in case 2 can be explained as the component of actual 'cross-flow' vibrations in 'x' direction (still referred to as in-line direction). As a result, the second modal weight of cross-flow displacement become smaller compared to that in case 1. For case 2, the riser does not necessarily cross the wake, rendering less intense vibrations compared to case 1, in which the riser is excited in only one direction. Comparing results of case 2 and 3, it is safe to say that the almost same forward and backward trajectory, which ensures that the riser crosses the wake, greatly enhance the vibrations.

Conclusions

The vortex-induced vibrations of a flexible riser excited at the top-end in one and two directions have been numerically simulated. A CFD method based on the strip theory is used in the simulations. Three cases are considered, one with only one-direction excitation, one with '∞'-shaped excitation trajectory, and one with parabolic excitation trajectory. When the riser was excited in a parabolic trajectory, the vibrations in both directions are enhanced. However, vibrations can be reduced in the '∞'-shaped trajectory case, in which a 'hat'-shaped trajectory has been observed（viewed from a reference frame which moves with the straight riser axis）. The key factor is whether the riser would cross its own wake.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (51379125, 51490675, 11432009, 51579145), Chang Jiang Scholars Program (T2014099), Shanghai Excellent Academic Leaders Program (17XD1402300), Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning (2013022), Innovative Special Project of Numerical Tank of Ministry of Industry and Information Technology of China (2016-23/09) and Lloyd's Register Foundation for doctoral student, to which the authors are most grateful.

References

[1]. Duggal, A.S., Niedzwecki and J.M. (1995) Dynamic response of a single flexible cylinder in waves, *J. Offshore Mech. Arct. Eng.* 117, 99–104.

[2]. Park, H.I., Hong, Y.P., Nakamura, M. and Koterayama, W. (2002) An Experimental Study on Transverse Vibrations of A Highly Flexible Free-Hanging Pipe in Water, in: *Proceedings of The Twelfth (2002) International Offshore and Polar Engineering Conference*. Kitakyushu, Japan, pp. 199–206.

[3]. Park, H.I., Hong, Y.P., Nakamura, M. and Koterayama, W. (2004) Experimental Study on Vortex Induced Vibrations of Highly Flexible Immersed Pipe Subjected to Top End Oscillations, *J. Waterw. PORT, Coast. Ocean Eng.* 130, 207–214.

[4]. Senga, H., Koterayama and W. (2005) An Experimental and Numerical Study on Vortex Induced Vibrations of a Long Flexible Riser Undergoing Irregular Motion at its Top End, *Int. J. Offshore Polar Eng.* 15, 274–281.

[5]. Riveros, C.A., Utsunomiya, T., Maeda, K. and Itoh, K. (2009) Dynamic response of oscillating flexible risers under lock-in events, *Int. J. Offshore Polar Eng.* 19, 23–30.

[6]. Duan, M., Wan, D. and Xue, H. (2016) Prediction of response for vortex-induced vibrations of a flexible riser pipe by using multi-strip method, Rhodes, Greece, pp. 1065–1073.

[7]. Fu, B., Duan, M. and Wan, D. (2016) Effect of mass ratio on the vortex-induced vibrations of a top tensioned riser, in: *The Second Conference of Global Chinese Scholars on Hydrodynamics Effect*, Wuxi, China, pp. 431–435.

[8]. Willden, R.H.J. and Graham, J.M.R. (2004) Multi-modal Vortex-Induced Vibrations of a vertical riser pipe subject to a uniform current profile, *Eur. J. Mech. B/Fluids* 23, 209–218.

[9]. Clough, R.W. and Penzien, J. (2003) Dynamics of Structures, 3rd ed, *Computers & Structures*, Inc., Berkeley.

[10]. Jasak, H. (2009) Dynamic Mesh Handling in OpenFOAM, in: *47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition*. American Institute of Aeronautics and Astronautics, Inc., Orlando, Florida.

[11]. Lie, H. and Kaasen, K.E. (2006) Modal analysis of measurements from a large-scale VIV model test of a riser in linearly sheared flow, *J. Fluids Struct.* 22, 557–575.

[12]. Trim, A.D., Braaten, H., Lie, H. and Tognarelli, M.A., 2005. Experimental investigation of vortex-induced vibration of long marine risers, *J. Fluids Struct.* 21, 335–361.