Proceedings of 7th PAAMES and AMEC2016
13-14 Oct., 2016, Hong Kong

Study of Loads and Response on Flexible Riser in Numerical Tank Combined with Wave and Current

WU Zi-xin[1] ZHU Ren-qing[2]

[1] Shanghai Ship & Shipping Research Institute, Shanghai 200135, China
[2] Jiangsu University of Science and Technology, Jiangsu Zhenjiang 212003, China

Abstract

By using the two-way coupling separation theory, transferring the data of the fluid domain and structure domain in the System Coupling module, the motion of a flexible riser with length-diameter ratio of 103 in the numerical wave/wave-current tank was simulated on the platform of Workbench 14.5. The fluid domain was established in Fluent module with the help of UDF programs. The tanks were simulated by velocity boundary method and wave-absorbing function was realized by the damping wave method. VOF technique was adopted to track the free surface. The calculation of the structure was implemented in Transient Structural module and the structure response was analyzed employing finite element method based on three dimensional solid element. The loads and response on flexible risers were analyzed and the result showed that the current displayed significant influence in the wave-current. Besides, the changes of motion of the riser and stress on it were different when the wave and current had different directional relations.

Keywords: Numerical tank, Flexible riser, length-diameter ratio, Fluid-Structure Interaction, Loads and response

1 Introduction

The marine riser is a pipeline connecting the offshore platform and seafloor equipment. It is easily damaged in the harsh marine environment especially under the combined effects of wave and current. With the continuous development of the deep sea resources, the research of the motion response of the marine riser has become a hot spot.

A lot of relevant researches have been made by a great many scholars in this field. In 1950, Morison et al. figured out the equation to calculate wave loads on rigid cylinder which was perpendicular to the seafloor by model tests which laid the theory foundation in engineering applications for the subsequent decades. In 1959, MacCamy and Fuchs gave analytic solutions to the linear wave force on a large diameter cylinder which stands from seabed to the surface. In 1976, Chakrbrti proposed a calculation formula to solve the nonlinear wave force by using Stokes nonlinear wave theory. In 2009, Keulegan and Carpenter analyzed the change rule of drag and inertia force coefficient of cylinder which provided reference for further work.

For the cases where wave and current both exsit, Sarpkaya analysed the change of drag coefficient of the cylinder in the wave tank. Wang Tao et al. presented a method to determine the hydrodynamic coefficient of structure in wave-current tank by using the results of which in pure wave and pure current on the theoretical basic of the interaction of wave and current. Han and Benaroya studied the axial and cross-flow vibration characteristics of marine riser which was fixed in the bottom and simply supported in the top under the combined effect of wave and current by using the Hamiliton principle and the Kirchhoff hypothesis.

With the development of commercial software, numerical simulation has become a popular choice in hydrodynamic research. A.S.Atadan studied the response of the marine riser in wave-current tank by adopting the numerical method based on the nonlinear elastic theory. In addition, Li Junqiang did some research on the nonlinear dynamic response of marine riser in deepwater by using software such as Ansys, Abaqus/Aqua, etc. Fluent was used by Wei to investigate the press on a rigid riser which had a length-diameter ratio of 8 in the wave-current tank.

Up to now, researches mainly focused on rigid risers. However, the riser with large length-diameter ratio would vibrate clearly in real marine environment. Hence it is more significant to do research on the loads and response on the flexible riser with large length-diameter ratio. In this paper, based on the viscous flow theory and time domain method, N-S equations of the incompressible fluid and structural dynamic equation, the viscous numerical wave and wave-current tank with the riser which has the length-diameter ratio of 103 were established. The loads and response on the flexible riser were analyzed.

2 Mathematical model

For incompressible fluid, continuity equation is

$$div(\boldsymbol{v}) = 0 \tag{1}$$

Where $\boldsymbol{v}$ is velocity vector of the flow.

When the fluid viscosity coefficient is constant, N-S equation is simplified as

$$\rho \frac{\mathrm{D}\boldsymbol{v}}{\mathrm{D}t} = \rho \boldsymbol{F}_b - \mathrm{grad}\, p + \mu \nabla^2 \boldsymbol{v} \tag{2}$$

Where ρ is fluid density, $\boldsymbol{F}_b$ is force, p is pressure, μ is dynamic viscosity coefficient.

For a linear elastic structure discretized by finite element, the dynamic equation is

$$[\boldsymbol{M}]\{\ddot{x}\} + [\boldsymbol{C}]\{\dot{x}\} + [\boldsymbol{K}]\{x\} = \{F(t)\} \tag{3}$$

Where $[\boldsymbol{M}]$ is mass matrix; $[\boldsymbol{C}]$ is damping matrix; $[\boldsymbol{K}]$ is stiffness matrix; $\{x\}$ is node displacement array; $\{F\}$ is equivalent node array synthesis of external forces.

An infinite-depth wave tank is simulated in this paper.

Wave profile is

$$\eta = \frac{H}{2}\cos(kx - \omega t) \tag{4}$$

Velocity potential is

$$\phi = \frac{gH}{2\omega} e^{kz} \sin(kx - \omega t) \tag{5}$$

Velocity in x is

$$u_x = \frac{H}{2}\omega e^{kz}\cos(kx - \omega t) \tag{6}$$

Velocity in z is

$$u_z = \frac{H}{2}\omega e^{kz}\sin(kx - \omega t) \tag{7}$$

The wave absorber at the end of wave tank is necessary to eliminate the wave reflection when the wave reaches the wall in a numerical wave tank. The wave-absorbing methods that are usually used are damping technique and porous media technique. Damping technique is adopted in this paper. In the wave-absorbing region, the momentum equations are as follows:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \upsilon\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2}\right) - C(x)u \tag{8}$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + w\frac{\partial w}{\partial z} = g - \frac{1}{\rho}\frac{\partial p}{\partial z} + \upsilon\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial z^2}\right) - C(x)w \tag{9}$$

Where $C(x)$ is wave attenuation coefficient as given below and υ is kinematical viscosity coefficient.

$$C(x) = c\sqrt{\lambda}\left(\frac{x - x_0}{x_L - x_0}\right)^2 \rho \tag{10}$$

According to the experience and numerical test, 10 is taken as the value for coefficient c; λ is wavelength; x_0 and x_L are the coordinate values of left and right boundary of the wave-absorbing region respectively; ρ is fluid density.

For both the accuracy and the need of the project, the wave-current superposition method proposed by Yu-Cheng Li is usually used for the combination of wave and current. The equation is given as:

$$u_{wc}(x,z,t) = u_w(x,z,t) + u_c \tag{11}$$

Where $u_{wc}(x,z,t)$ is the wave-current velocity; $u_w(x,z,t)$ is the wave velocity; u_c is the current velocity.

The wave parameters are listed in Table 1:

Table 1 Wave parameters of cosine wave

case	λ(m)	A(m)	c(m/s)	T(s)
0	20.0	0.5	5.59	3.58

Three cases are chosen in the paper which is shown in Table 2.

Table2 The velocity of wave and current

case	u_w (m/s)	u_c (m/s)	u_c / u_w
1	5.59	0	0
2	5.59	1.118	20%
3	5.59	-1.118	-20%

3 Model establishment and calculation settings

The numerical model is built in the Geometry module in which the domain is $80m \times 10m \times 103m$, water depth is 100m, the area above the water is filled up with air and the rightmost 20m of the tank is wave-absorbing region. Figure 1 is the schematic diagram. The left boundary is velocity-inlet, the right is pressure-outlet, the top is pressure-inlet and the other sides are stationary wall.

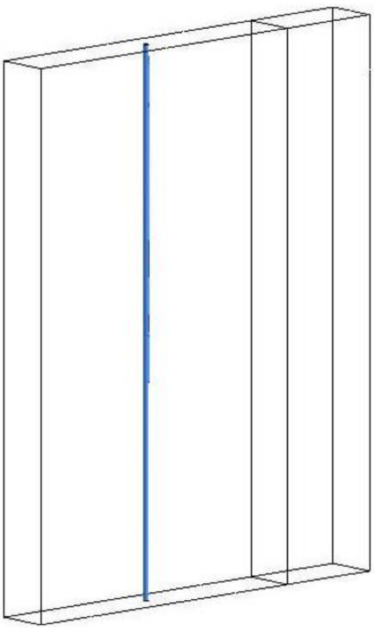


Figure 1. Schematic diagram of the tank

The fluid domain is discretized in Mesh module. A single grid length is taken as $\lambda/100$ in wavelength direction. Mesh is refined between one wave height up and down the calm water surface along water depth in order to track the free surface accurately and the grid height is 1/20 of the wave amplitude. Mesh size gradually increases within 10m below the free surface. Seven layers mesh divided the rest domain underwater because the wave effect is much smaller in that part. The mesh around the riser is refined for the solution accuracy of fluid field. Figure 2 is the mesh diagram.

The parameters of the riser are listed in Table 3. The riser has a distance of 30m from the inlet wall, and 5m from the two side walls. The gravity is 9.8m/s^2. The displacement of the top of the riser is limited on the horizontal direction and the bottom of the riser is simply supported.

The fluid calculation is realized in Fluent module and the vibration of riser is calculated in Transient Structural module. System Coupling module is used to transmit the data computed by the fluid and the structural domain simultaneously.

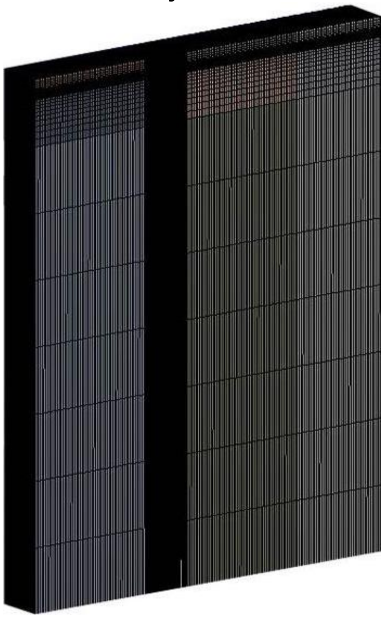


Figure 2. Schematic diagram of the mesh

Table 3 Parameters of the riser model

parameter	value
length L	$103m$
diameter D	$1m$
thickness Δ	$0.05m$
density	$7850 kg/m^3$
Young's Elastic Modulus E	2×10^{11} N/m^2
preloaded force	$3000000N$

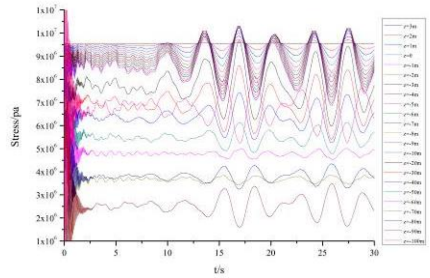
Calculation starts from the fluent domain. Simulation time is 30s and time step is 0.005s.

4 Analysis of the simulation results

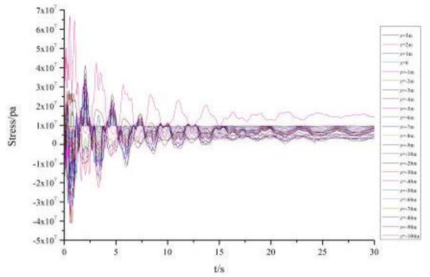
There are twenty-two points set to monitor the calculation results. The points are located every 1m above the position 10m below the static water, and every 10m from 10m to 100m under the water respectively.

4.1 Analysis of stress

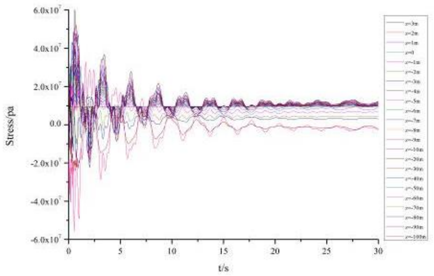
Figure 3 shows the stress on the riser.



(1) Case1



(2) Case2



(3) Case3

Figure 3. Stress on the riser

Figure 4 shows the maximum stress of the monitoring points. It is seen that the stress on the point of 70m under the water (point X) in different cases tend to be the same. Above point X, the stress in Case1 is bigger than that in Case2 while smaller than that in Case3. But the consequence is exactly the opposite under point X. In case3, pressure turns to be tension in the lowest end of the riser. The result indicates that the global stress on the riser moves down when the wave and current has the same direction and moves up when the direction is on the contrary.

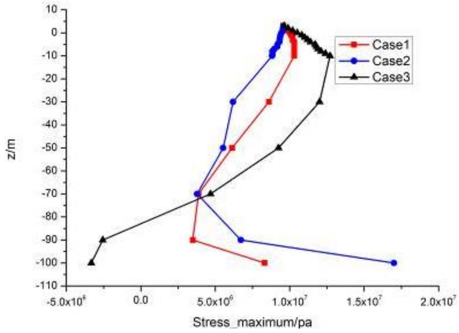


Figure 4. Maximum stress of the points

Dimensionless drag coefficient is expressed as

$$C_d = \frac{F_d}{\frac{1}{2}\rho v^2 S} \tag{12}$$

Where F_d is the horizontal force, S is projected area of the riser and was taken as $103m^2$.

Figure 5 is the duration trace of drag coefficient of the cases. These three curves have essentially the same cycle which is near the period of the wave. In Case 1, the value changes with a similar amplitude around the equilibrium point. In Case 2, the wave and the current have the same direction, drag coefficient is greater than that in Case 1, and in Case 3, where the directions of the wave and the current are opposite, drag coefficient is smaller than that in Case 1. That means the current has a significant influence on the force on the riser. Besides, it is noteworthy that the difference of drag coefficient between Case 1 and Case 2 is nearly the same as that between Case 1 and Case 3. This illustrates the current determines the average value of drag coefficient in the wave-current tank.

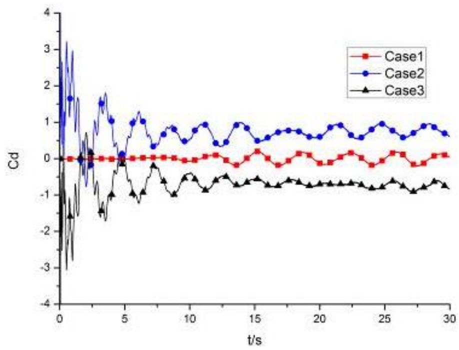
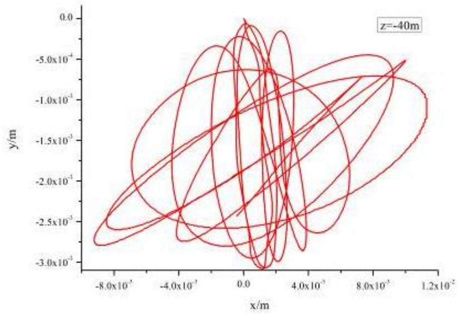


Figure 5. Drag coefficient of the cases

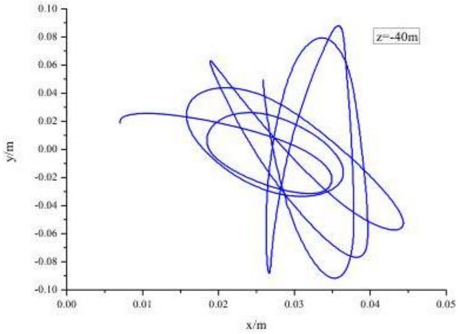
4.2 Analysis of motion

The movement tracks of the monitoring

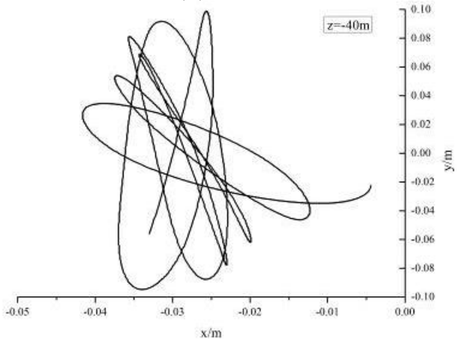
points 40m below the water of the three cases are shown in figure 6. And the motion generally goes with the direction of the current.



(1) Case1



(2) Case2

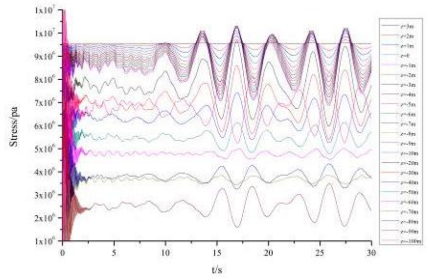


(3) Case3

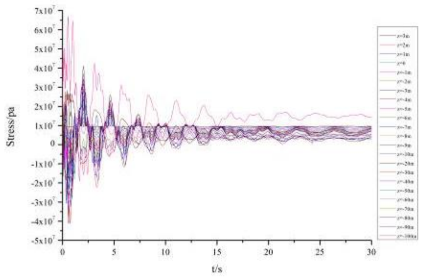
Figure 6. Movement tracks of the monitoring points

4.2.1 In-line motion analysis

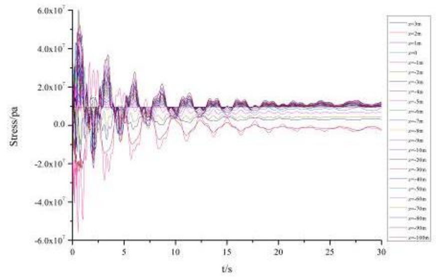
Figure 7 presents in-line motion of the monitoring points. In the wave tank, the amplitude is basically symmetrical in the initial position. And in wave-current tank, the amplitude goes with the direction of the current compared to that in the wave tank. Figure 8 shows in-line amplitude of the monitoring points. It is shown that the maximum amplitude is in 30m below the water and moves to 40m below the water in wave-current tank which is consistent with the conclusion in reference. The amplitude in Case 1 is 0.568 times than that in Case 2 and 1.25 times than that in Case 3. This embodies the influence of the combined effect of wave and current.



(1) Case1



(2) Case2



(3) Case3

Figure 7. In-line motion of the monitoring points

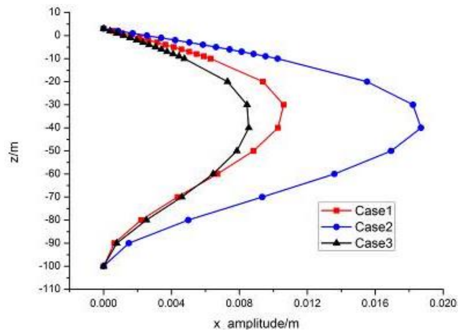
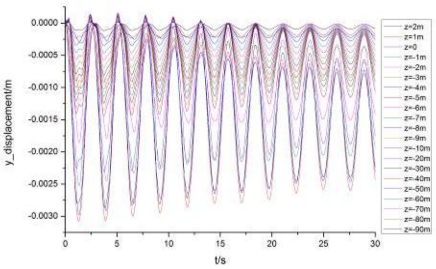


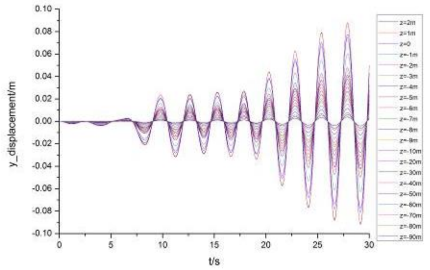
Figure 8. In-line amplitude of the monitoring points

4.2.2 Cross-flow motion analysis

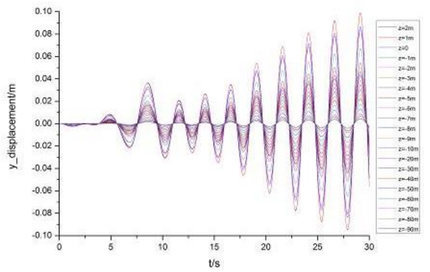
Figure 9 shows cross-flow motion of the monitoring points. In Case 1, the amplitude is a small quantity compared to that in Case 2 and Case 3. In wave-current tank, every point in the riser moves to one direction in the same moment. And it can be seen that the maximum amplitude is 40m below the water which is similar to the phenomenon of in-line motion. The significant effect of current can be found by comparing the wave tank to the wave-current tank.



(1) Case1



(2) Case2



(3) Case3

Figure 9. Cross-flow motion of the monitoring points

4.2.3 Axial motion analysis

The length of the riser is used as horizontal coordinate and amplitude of the monitoring points as the vertical coordinate, and the result is shown in figure 10. It is seen that the amplitude performance of the risers in three cases is similar to each other. The least amplitude happenes in the bottom and there are two turning points nearly 60m and 35m below the water and then the amplitude increases with the height of the riser and finally gets the maximum value on the top. This means in engineering issues that some measures should be taken in the special positions.

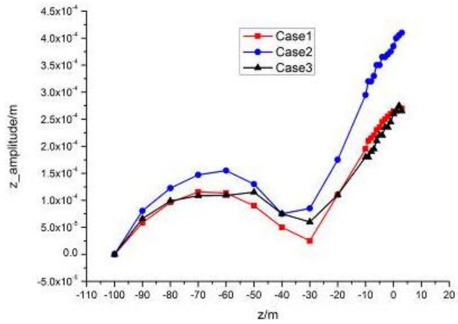


Figure 10. Axial amplitude

5 Conclusions

The platform of Workbench was used to simulate the tank with a large length-diameter ratio flexible riser. In wave-current tank, the balance of the in-line vibration went with the direction of the wave, the cross-flow vibration expressed a significant motion compared to the wave tank. When wave and current had the same direction, the overall pressure on the riser moved downward, the in-line and axial amplitude increased. When the directions of wave and current were opposite, the overall pressure moved upward, the in-line amplitude decreased while the axial amplitude did not change a lot. Besides, two turning points were analyzed which should be paid attention to in projects.

References

Morison J R, O'Brien M P, Johnson J W, et al. The force exerted by surface waves on piles. Petrol. Trans., 1950, l89, 149-154.

MacCamy R C, Fuchs K A. Wave force on piles: a diffraction theory. Beach Erosion Board, 1954, 1-69.

RAHUL A. BIDKAR, MARK KIMBER, ARVIND RAMAN et al. Nonlinear aerodynamic damping of sharp-edged flexible beams oscillating at low Keulegan-Carpenter numbers[J]. Journal of Fluid Mechanics,2009,634:269-289.

Sarpkaya T,Bakmis C, Storm M A. Hydrodynamic forces from combined wave and current Flow on smooth and rough circular cylinders at high Reynolds number. Proceeding of 16th OTC, Houston,1984.

Sarpkaya T. In-line force on a cylinder translating in oscillatory flow. Applied Ocean Research, 1985,7(4):188-196.

Wang Tao, Li Jiachun. Application of conservation law of wave action flux to wave current interaction.[J] Acta Mechanica Sinica, 1996, 28(3): 281-290.

Han S M, Benaroya H. Non-linear coupled transverse and axial vibration of a compliant structure, Part 1: Formulation and free vibration[J]. Journal of sound and vibration, 2000, 237(5): 837-873.

Atadan A S, Calisal S M, Modi V J, et al. Analytical and numerical analysis of the dynamics of a marine riser connected to a floating platform[J]. Ocean Engineering, 1997, 24(2): 111-131.

Li Junqiang, Liu Hongzhao, He Qingxiang. On Random Vibration of Riser System in Marine Drilling Subjected to Wave Force.[J] Mechanical science and techonology, 2004, 23(1): 7-10.

Wei Chengxun. Numerical simulation of combined actions of wind, wave and current and their actions on cylindrical component.[D] Harbin Institute of Technology, 2012.

Li Yucheng .The velocity field under influence of wave and current[J]. The Ocean Engineering, 1983, (4):12-23.

Wang Chengguan. Study on three dimensional numerical simulation of VIV characteristics for marine riser.[D] Shanghai Jiaotong University, 2011.