Experimental study on a new riser in large flume under the influence of wave and current

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Abstract. The traditional riser system needs to recover all the risers when typhoon comes, which often takes a long time and high risk. In recent years, a new type of anti-typhoon riser system emerged, which can realize the emergency separation of the upper offshore platform and the lower riser system near the water surface, and the remaining riser can stand in the deep water freely through the net buoyancy provided by the buoy. In order to verify the feasibility of the new anti-typhoon riser system, the vortex induced response of the riser under the combined action of wave and current is studied by physical model test in large flume with geometric scale of 1:21 under three different net buoyancy conditions; The results show that the net buoyancy of the buoy has a great influence on the natural frequency and motion response of the new riser. Under the combined wave current condition, the wave restrains the vortex induced motion of the riser in a certain extent and reduces its overall offset.

1. Introduction

With the development of oil and gas exploration and development into the deep sea, waves and currents become the most concerned load sources in the offshore structures. When the water flows through the slender and flexible riser structure, the vortex shedding will be formed on both sides of the riser, which will produce periodic force in the cross flow, and then cause the vortex induced vibration (VIV) of the riser [1]. VIV characteristics of deep-sea flexible risers with large aspect ratio have attracted extensive attention of scholars at home and abroad. Liu et al. [2] summarized the basic research results of VIV of deep-sea flexible risers with large aspect ratio have attracted extensive attention of scholars at home and abroad. Liu et al. [2] summarized the basic research results of VIV of deep-sea flexible risers with large aspect ratio. In recent years, including the research progress of VIV of multiple risers and inclined risers, intermittent VIV caused by oscillating flow, etc., and prospected the future research direction. In terms of numerical research, Wu et al. [3] used VIV-FOAM-SJTU to study the vortex induced vibration of tandem double risers with different immersion lengths. Li et al. [4] studied the influence of mass ratio and damping ratio on high damping vortex induced vibration by establishing a single degree of freedom VIV model. Xu et al. [5] established a prediction model for VIV of submarine suspended pipeline considering fluid-solid-soil interaction, and focused on many characteristics of vortex induced vibration of suspended pipeline. In terms of physical model research, Ma et al. [6] studied the VIV performance of double rectangular cross-section under different constraint conditions through experiments, and found that the influence
of fixed section on VIV of downstream section was more significant. Song et al. [7] studied the VIV of a long flexible riser towed horizontally at different uniform velocities through flume experiments. Xu et al. [8] further studied the multi-mode VIV characteristics of a long flexible riser with inclined towing under different current angles on the basis of song et al. [7]. Gu et al. [9] studied the effect of internal friction on VIV, and measured the vortex induced response of the model using fiber Bragg grating strain sensor (FBG).

It can be found from the above studies that the VIV characteristics of deep-sea risers are simplified to beam structures with fixed ends or simply supported in both physical and numerical models. However, there are few studies on the motion characteristics of free-standing risers. and few scholars have studied the response of riser under the action of wave and current. In order to further study the VIV characteristics of offshore risers, a physical model test of a new type of anti-typhoon riser was designed based on the size of large-scale wave flume. The motion response of the riser with different buoyancy under the combined action of wave and current is studied, and the research results can provide a reference for the design of the new type of anti-typhoon riser.

2. Experimental methods

2.1. Coordinate system

In the test, x-axis is positive along the reverse direction of water flow, z-axis is positive along the riser, Y-axis is defined by the right-hand rule, the coordinate origin O is located at the bottom baseline of the riser, x-axis is in-line (IL-direction) and y-axis is cross-flow (CF direction) of riser. In order to measure the strain of riser, 20 FBG sensors are arranged around the riser, as shown in Figure 1. In addition, according to the estimated structural mode, the specific installation positions of FBG sensors along z direction are shown in Table 1.

| IL direction | number | G01 | G02 | G03 | G04 | G05 | G06 | G07 | G08 |
|--------------|--------|-----|-----|-----|-----|-----|-----|-----|-----|
| position     |        | 1.1 | 1.7 | 2.5 | 3.3 | 4.3 | 5.2 | 6.0 | 6.8 |

| CF direction | number | G01 | G02 | G03 | G04 |
|--------------|--------|-----|-----|-----|-----|
| position     |        | 1.7 | 2.5 | 4.3 | 6.0 |

Table 1. FBG sensor installation position (unit: m)

![Figure 1. Test coordinate system and sensor system installation location](image)

2.2 Model scale design

According to the parameters of the prototype riser and the size of the wave tank, the geometric scale is determined as $\lambda = 21$. In order to accurately simulate the hydrodynamic load and deformation characteristics of the riser, it is necessary to design according to the actual structure by gravity similarity and geometric size similarity, and the specific parameters are shown in Table 2.
In the experiment, PE pipe, aluminum tube and lead rod combined casing were used to ensure the similar bending stiffness. The bending stiffness of the combined casing is measured by four-point method. Section 3.1 introduced specific measurement methods and results. A plexiglass pipe is sheathed on the outside of the combined casing to ensure that the outer diameter and size of the drag are similar, and the force is transferred to the combined casing through the inner flange. Three sections of solid floating material (material density of $0.21 \times 10^3$ kg / m$^3$) are used to simulate the floating structure, so as to provide buoyancy for the riser.

| Parameter                      | Prototype value | Scale | Model value   |
|--------------------------------|-----------------|-------|---------------|
| Material outer diameter        | 21 inch, 0.5334 m | 21    | 0.0254 m     |
| Drag force outer diameter      | 54 inch, 1.3716 m | 21    | 0.065 m      |
| Bending stiffness              | $2.418 \times 10^8$ N·m$^2$ | 21$^3$ | 59.20 N·m$^2$ |
| Unit wet weight                | 119.6 kg/m$^3$/m | 21$^2$ | 0.271 kg/m$^3$/m |
| Outer diameter of floating body| 14 inch, 4.2672 m | 21    | 0.203 m      |
| Length of floating body        | 180 inch, 54.864 m | 21    | 2.613 m      |
| Floating body spacing          | 15 inch, 4.572 m  | 21    | 0.218 m      |
| Provide buoyancy               | $3.765 \times 10^9$ N | 21$^3$ | 403.56 N     |

2.3 Experimental conditions
According to the actual needs, 8.0 m water depth is adopted in the test. Considering the combined action of wave and current, the tests are carried out for different buoy net buoyancy 403.5 N (full buoyancy), 322.8 N (80% buoyancy), 242.1 N (60% buoyancy). The significant wave height is 0.409 m and peak period is 2.12 s. Three current velocities are carried out in the experiment, which are 0.137, 0.151 and 0.182 m/s, respectively.

2.4 Experimental data processing method
During the experiment, the vibration response of the riser will occur under different working conditions. Through the fiber Bragg grating strain sensor, the strain change of the riser model in the vibration process can be observed in real time, and then the measured strain signal is converted into displacement response through the method of modal decomposition, and then the physical law of vortex induced vibration is studied. The free-standing riser can be simplified as a cantilevered Bernoulli-Euler beam.

3. Results and analysis
3.1 Results of bending stiffness
In order to ensure that the bending stiffness of the riser meets the design requirements, a composite casing whose length is one meter was taken for bending stiffness test. The specific test method is four-point method, as shown in Figure 2-a. LVDT displacement sensor was used to measure the deflection of the position at the hanging weight. Figure 2-b showed the displacement curve under different hanging weights. The bending stiffness was 56.8 N·m$^2$ according to the experiment. Compared with the design value, the error was less than 5%, which met the requirements.
3.2 Experimental results

Figures 3 and 4 show the displacement time history curves and amplitude spectrum of each measuring point under two kinds of buoyancy conditions when the current velocity is 0.137 m/s combined with wave, where \( x / D \) and \( Y / D \) are dimensionless displacements in IL and CF directions respectively, and \( D \) is the diameter of riser. It can be seen from the amplitude spectrum that under the combined action of wave and current, the main frequency of wave is 0.45 Hz in the IL and CF directions. When the net buoyancy increases to 100\%, due to the large overall stiffness of the riser at this time, the impact of the current is small, and the dynamic response of the riser is affected by the wave.
Statistical analysis was also carried out in the test results. The average value of time histories (represented by Ave in the figure) were used to describe the displacement of different positions of the pipe body in the IL direction; the root mean square (RMS) of the time histories curve were used to describe the vibration of the riser at different positions under different buoyancy and velocity conditions in the CF direction; the specific statistical results were obtained in Figure 5.

According to the statistical analysis, when the floating body provides the same buoyancy along the flow direction, the motion response amplitude of each measuring point of the riser increases with the increase of velocity. When the velocity is the same, the response amplitude of each measuring point decreases with the increase of buoyancy provided by the floating body. To some extent, the existence of waves suppresses the VIV of the new riser and reduces the deviation along the flow direction of the riser. In the CF direction, the maximum displacement of the riser does not appear at the top measuring point of the riser under the combined action of wave and current in the case of 100% buoyancy, which
also shows that the wave has a certain inhibitory effect and the vibration mode of the riser in the CF direction is controlled by wave mode. In addition, it can be seen from Figure 5-b that with the decrease of buoyancy, the dominance of wave frequency is weakened. When the buoyancy provided by the floating body is 60%, the maximum displacement of the riser appears at the measuring point at the top of the riser again.

4. Conclusion
In this paper, the VIV of a new type of anti-typhoon riser under the combined action of wave and current is studied by large-scale physical model test, and the conclusions are as follows:

1) Under the joint action of waves and currents, the motion responses at different positions of the riser decreases with the increase of buoyancy, and the natural frequency of the riser also increases accordingly. Therefore, by adjusting the buoyancy of the floating blocks, the resonance induced by natural frequency of the riser and the excitation frequency of the environmental load can be avoided, so as to ensure the safety of the structure.

2) Under the joint action of wave and current, the existence of wave can restrain the VIV at the top of the riser in a certain extent, and reduce the overall movement of the riser.

3) Under the combined action of wave and current, with the increase of buoyancy, the wave frequency gradually becomes the dominant frequency to control the vibration response of riser, and the maximum displacement of riser does not appear at the top measuring point.

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References
[1] Tang G.Q., Lu L., Teng B., et al. (2011) Vortex-induced vibration experiment of flexible rod with large slenderness ratio. Ocean Engineering, 29(01):18-25.
[2] Liu G.J., Li H.Y., Qiu Z.Z., et al. (2020) A mini review of recent progress on vortex-induced vibrations of marine risers. Ocean Engineering, 195, 106704.
[3] Wu L., Zhao W.W., Wan D.C. (2020) Numerical simulation of vortex induced vibration of double risers with different submergence lengths. Ocean Engineering, 38(03): 52-61.
[4] Li X.C., Zhou X.P., Zhao L.P. Effects of mass ratio and damping ratio on high damped vortex-induced vibration [J]. Ship Mechanics, 2018, 22(02):165-173
[5] Xu W.H., Xie W.D., Gao X.F., et al. (2018) Study on the Vorticity induced vibration characteristics of cantilever pipe considering soil action. Ship Mechanics, 22 (04): 446-453.
[6] Ma K., Hu C.X., Zhou Z.Y. (2020) Analysis of Vortex Vibration Performance of Double Rectangular Sections under different constraints. Vibration and Impact, 2020, 39(10): 141-147+205.
[7] Song J.N., Lu L., Teng B., et al. (2011) Laboratory tests of vortex-induced vibrations of a long flexible riser pipe subjected to uniform flow. Ocean engineering, 38(11-12): 1308-1322.
[8] Xu W.H., Ma Y, Ji C, et al. (2018) Laboratory measurements of vortex-induced vibrations of a yawed flexible cylinder at different yaw angles. Ocean Engineering, 154: 27-42.
[9] Gu H.L., Guo H.Y., Liu Z., et al. (2020) Experimental Study and Fatigue Analysis of Vortex-Induced Vibration of Umbilical Cable Considering Internal Friction. China Ocean Engineering, 34(02): 151-161.