Study on vortex-induced vibration of non-uniform flow riser based on fluid-solid coupling

Lin Tiejun¹, Bao Xiaomin¹*, Zhou Xu², Zuo Jinju¹, Mou Yisheng¹

¹ State Key Laboratory of Oil and Gas Reservoir Geology and Exploration, Southwest Petroleum University, Chengdu, Sichuan, 610500, China
² Craft and Hawkins Department of Petroleum Engineering, Louisiana State University, Baton Rouge, LA 70803, USA

*Corresponding author’s e-mail: bxm1201@163.com

Abstract. Because marine riser is under complex ocean current environment, fatigue damage tends to happen due to vortex-induced vibration, which has a strong impact on the safety issue of deepwater drilling and completion. Vortex-induced vibration (VLV) induced by non-uniform flow loads on deep water riser coupling in complex Marine environments has been studied relatively infrequently at home and abroad. Therefore, CFD-FEM bidirectional fluid-solid coupling method was used to establish a vortex-induced vibration model of 1500m deep water riser and non-uniform flow in waves and currents. Vortex-induced vibration and mechanical behavior of riser in transverse and flow direction were studied from riser motion characteristics, tension factors and other aspects. The results show that the danger zone of vortex-induced vibration of riser under the action of non-uniform flow occurs in one third of the upper end. Increasing the tension can increase the riser's natural frequency and reduce the amplitude of vortex-induced vibration, but may aggravate the riser's high stress and low cycle fatigue damage.

1. Introduction
As China's external dependence on oil and gas approaches 70%, it is necessary to increase efforts to accelerate the exploration and development of complex deep-sea conditions. 500-3000m deep-sea offshore oil and gas will be the focus of oil exploration and development[1], China's South China Sea will be the main battlefield. In the process of deep-water drilling, the riser is an indispensable important component, but it will be affected by external factors such as floating drilling platform drift, top tension, and marine environmental load[2]. Under the action of complex non-uniform flow such as wind, waves, and currents, the slender and flexible deep-water riser may experience vortex-induced vibration fatigue, damage, leakage, and breakage[3].

A large number of studies have been carried out by domestic and foreign scholars on the vortex-induced vibration phenomenon of the riser. In 2005, Kaewunruen applied the finite element method to analyze the nonlinear dynamic response of the riser, considering the influence of internal fluid on the dynamic characteristics of the riser[4]. In 2006, Pereira studied the dynamic behavior of vertical riser with floating body, considering the hydrodynamic effect of waves and currents and the influence of floating body size[5]. In 2010, Cai Jie used large eddy simulation method to conduct three-dimensional numerical simulation of the flow field and finite element method of thin shell model to conduct numerical calculation of structural vibration[6]. In 2013, Lin Lin used the finite element method to study the multi-mode vortex-induced vibration response of the riser under the action of shear flow, and
compared the different response characteristics of the riser under the condition of uniform flow and shear flow[7]. In 2014, Liu Qingyou used the minimum micro-element method to analyze the influence of drilling conditions such as drill string and drilling fluid displacement on the deformation of the riser[8]. In 2018, Zhu Hongjun used the CFD method to study the vortex-induced vibration and suppression of the riser and surrounding auxiliary pipelines, and analyzed the influence of the installation position and shape of the strip on the vortex-induced vibration of the riser[9]. It can be seen that the vortex-induced vibration of the riser has been a hotspot in deep water drilling research. The CFD method is mainly used to study the effect of uniform flow on the riser.

At present, there are few researches on the vortex-induced vibration of the deep-water drilling riser under non-uniform flow in the complex marine environment. However, the non-uniform flow load of the combined action of the ocean wave and the ocean current is closer to the real situation and meets the actual working conditions. Therefore, based on the marine environmental wave and current data in a certain area of the South China Sea, this paper studies the vortex-induced vibration phenomenon and the mechanical behavior of the riser under the coupling action of non-uniform current load on the 1500m depth riser, so as to provide support for more reasonable vortex-induced vibration suppression measures and device research.

2. Mechanical load of riser structure
The loads on the deep-water drilling riser mainly include the marine environmental load, the top tension of the riser, the inertial load of the internal fluid, and the floating weight of the riser, as shown in Figure 1. Taking the sea level of the riser as the coordinate origin, the vertical direction is the z-axis positive direction, the ocean load wave flow direction (flow direction) is the x-axis positive direction[10], and the horizontal vertical current direction (lateral direction) is the y-axis direction. The wave load acts periodically at a certain depth in the sea level, and the current load changes along the vertical direction.

2.1. Wave load
Compared with the ocean area and water depth scale, the deepwater drilling riser is a small diameter tubular structure. Therefore, the Airy linear wave theory is used to characterize the wave velocity, and the Morison equation is used to calculate the wave force $F_{wa}$ including the drag force and the inertial force. The Morison formula is as follows:

$$F_{wa} = \frac{1}{2} \rho_w C_D D (u + v) |u + v| + \rho_w C_M \frac{\pi D^2}{4} \frac{\partial u}{\partial t}$$  \hspace{1cm} (1)

Where $\rho_w$ is the density of seawater, kg/m$^3$; $D$ is the diameter of the riser, m; $u$ is the motion velocity of drop of water perpendicular to the riser, m/s; $\partial u/\partial t$ is the acceleration of drop of water, m/s$^2$; $C_D$ is the resistance coefficient, and the value range is 0.4-1.6; $C_M$ is the mass inertia force coefficient, and the value range is 0.93-2.3.

The density of seawater in a certain area of the South China Sea is 1030 kg/m$^3$, and the dynamic viscosity coefficient is 1.1055×10$^{-3}$ Pa*s. Under non-extreme conditions, the wave height is 4m, the wave period is 11.2s, and the flow rate is 1.8m/s. At a flow rate of 0.01-2.3m/s, the lift coefficient of the riser is 0.2-0.6, and the drag coefficient is 0.3-1.
2.2. Current load

Formula (2) used by the US Bureau of Surveying Ships is adopted to calculate the current velocity below the sea surface[11]:

\[ v = v_m \left[ \frac{h}{H} \right] + v_t \left[ \frac{h}{H} \right]^\gamma \]  

(2)

Where \( v_m \) is the wind velocity of the sea surface, m/s; \( v_t \) is the tidal current velocity of the sea surface, m/s; \( H \) is water depth, m; \( h \) is the depth from the sea bottom to the flow rate calculated position, m.

According to the ocean data of a certain area in the South China Sea, under the non-extreme condition, the annual average wind speed is about 3-5m, the average current velocity is about 0.5m/s in the surface layer, and decreases with the increase of the depth. The bottom flow velocity in the offshore is about 0.03m/s. According to this, the velocity distribution along the depth of the current in the target area can be established.

At different water depths, the flow rate is different, and the resulting lift is also different. The lift \( F_L \) per unit length of the riser as follows:

\[ F_L = \frac{1}{2} \rho C_L D u^2 \sin(\omega t) = \frac{1}{2} \rho C_L D u^2 \sin(2\pi ft) \]  

(3)

Where, \( C_L \) is the lift coefficient; \( \omega \) is the angular frequency of vortex shedding, and \( f \) is the frequency of vortex shedding.

3. Ocean - riser coupled vibration model

3.1. Coupled vibration mathematical model

The vortex-induced vibration of the deep-water drilling riser in the marine environment is a vibration system in which fluid interacts with solid structures. Fluid-solid coupling is a transient response and is often solved in the time domain. The six-degree-of-freedom rigid body motion model of the floating body is introduced into the elongated structural finite element (FEM) model to obtain a complete coupling system. The equation of the riser equation as follows:

\[ M \ddot{d} + K \dot{d} + C d = F(t) \]  

(4)

Where \( d, \dot{d} \) and \( \ddot{d} \) are the displacement, velocity and acceleration vectors at the unit node of the riser; \( F(t) \) is the external load vector at the unit node of the riser; \( M, C \) and \( K \) are the mass matrix, damping matrix and stiffness matrix.

By dividing the system matrix into floating body and slender structure for description, the motion equation of the coupled system can be rewritten as[12]:

\[
\begin{bmatrix}
M_f & 0 \\
0 & M_L
\end{bmatrix}
\begin{bmatrix}
\ddot{x}_f \\
\ddot{x}_L
\end{bmatrix} + 
\begin{bmatrix}
B_f & 0 \\
0 & B_L
\end{bmatrix}
\begin{bmatrix}
\dot{x}_f \\
\dot{x}_L
\end{bmatrix} + 
\begin{bmatrix}
K_f & 0 \\
0 & K_L
\end{bmatrix}
\begin{bmatrix}
x_f \\
x_L
\end{bmatrix} = 
\begin{bmatrix}
F_f \\
F_L
\end{bmatrix}
\]

(5)

Where, \( M_f \) is floating body mass matrix; \( M_L \) is the elongated structure mass matrix; \( B_f \) is the floating body damping matrix; \( K_f \) is the floating body stiffness matrix; \( F_f \) is the external force vector.

3.2. Coupled vibration CFD-FEM model

The CFD method is used to establish the marine environment fluid simulation of the riser. The fluid domain size is 40D×20D×20D, and D is the outer diameter of the riser. The FEM method is used to establish the riser structure model, and set up the CFD-FEM bidirectional coupling. The schematic diagram of the model is shown in Figure 2. The relevant parameters are shown in Table 1.
In the CFD model, complex flow phenomena such as boundary layer separation and vortex occur around the wall of the riser, and set boundary layer properties and grid encryption, so the grid on the riser surface is the densest, and a coarser mesh is used in areas where the flow velocity gradient does not change much. The surface ABEF is the velocity inlet boundary of the inflow at infinity, and the surface CDGH is the pressure outlet boundary of the free outflow. Using the k-ω turbulence model, the contact surface of the riser and the fluid is treated as a smooth cylindrical wall surface, and set as a two-way coupling surface, as shown in figure 2(a). In the FEM model, the riser bottom of the subsea wellhead is hinged and the top is the tension of the drilling ship. The outer wall of the riser is set to the bidirectional coupling surface corresponding to the CFD model, as shown in figure 2(b).

The CFD-FEM coupling model transfers the force and displacement of the riser from the marine fluid calculated by the CFD model to the FEM model as the boundary value of the outer wall of the riser. Under the joint action of other boundary conditions, the FEM calculates the displacement of the riser and transmits it to the coupled wall of the CFD model riser. In this way, the Marine flow field and the stress strain and vibration characteristics of the riser at different times are obtained by cyclic iteration.

### 4. Result analysis

#### 4.1. Analysis of riser motion characteristics

In the calculation of the FEM model, the effects of floating weight, top tension and coupling loads of ocean flow on the riser are considered, in which the distribution of ocean coupling loads in the vertical direction varies non-uniformly with time and water depth. Under the action of ocean vortex, the flow direction vibration of the riser presents a high-order vibration mode, and its maximum force occurs at about 400-600m below the sea level, that is, about one third of the upper end of the riser. The maximum position of the lateral vibration displacement occurs in the 400m well section above the bottom hinge, as shown in figure 3.
Figure 3. Vibration displacement diagram of riser at different moments

Under the action of ocean current load and vortex-induced vibration, the riser tube is bent in the x direction (flow direction) and the y direction (lateral direction). The maximum bending moment occurs in the 20-100m well section below the sea level and the 100m well section above the bottom hinge, which is the danger zone of the vortex lateral and flow direction vibration of the riser, as shown in figure 4. The transverse vortex-induced vibration of the riser is mostly of low order vibration mode, while the transverse and directional vibration natural frequencies of the slender riser are the same and both are low. Under the non-uniform flow ocean load, the local well vortex-induced resonance region is easy to be generated. Taken together, the top area is more dangerous.

Figure 4. Moment curve of riser at different moments

4.2. Influence of tension on vibration characteristics of riser

In the previous study, it was considered that the top tension was 1G, that is, the top lift tension was the floating weight of the riser, and the riser generated large vortex-induced vibration and lateral and directional vibration displacement under the action of non-uniform Marine environment load. In order to study the influence of top tension on vortex-induced vibration, the influence of 1G and 2G tension on riser vortex-induced vibration were compared.

Under the action of non-uniform ocean load, the riser flow direction vibration changes periodically, and the closer it is to the sea surface, the more it is affected by waves. It can be seen from figure 5(a) that riser is slowly approaching the stable vibration state after 60s. When the tension is 1G, the maximum displacement of the riser is about 0.9m, and the fluctuation is large. When the tension is 2G, the maximum deviation displacement of the riser is about 0.2m, which is about 80% lower than that when the tension is 1G, with small amplitude but high frequency. It shows that increasing the tension can reduce the riser's deviation from the maximum displacement and make it enter the stable vibration state in a short time.

As can be seen from figure 5(b), when the tension is 1G, the vortex drops off and the lateral vibration of the riser enters a stable vibration state after 60s, and its vibration amplitude is about 0.2m. However, when the tension is 2G, it enters the stable vibration state after 30s. Compared with the situation when the tension is 1G, the vibration amplitude decreases by about 90%. It shows that increasing the tension
can effectively reduce the lateral amplitude of the riser and shorten the time when the riser reaches a steady state.

In addition, analysis of the transverse and flow direction vibration displacements of the whole well riser at different times, and the vibration differences in the two directions are compared. As can be seen from figure 6(a), the flow direction displacement of the riser decreases significantly as the tension increases. The maximum displacement occurred in the upper third of the riser lower. When the tension is 1G, the flow direction vibration displacement is basically the same in the 400m well segment from the bottom of the riser, and the flow direction displacement fluctuates significantly in the well segment of 300-700m. When the tension is 2G, the fluctuation range of the entire riser section is relatively small. As can be seen from figure 6(b), the vibration of the riser in the lateral direction is complex, and the maximum displacement position is constantly changing. With the increase of tension, the lateral displacement of the riser at the same time decreased significantly. The maximum displacement at 20s is reduced from 0.4m to 0.0125m, which is reduced by about 75%. Therefore, increasing the tension may reduce the amplitude of the lateral vortex vibration and promote the riser to maintain a stable vibration state.

Under the two-way coupling of the marine and riser, the vortex-induced vibration of the riser reaches a steady state after 60s, the top stress of the whole well of the riser reaches the maximum, and the stress at the bottom of the riser is the smallest, as shown in Figure 7. As the top tension increases, the maximum stress of the riser increases from 182MPa to 363MPa, and the stress of the riser reaches 340MPa in the upper third of the water depth. For the commonly used X80 steel riser, when the top tension is 2G, the top stress of the riser reaches 60% yield strength. High frequency vortex-induced vibration may lead to high stress and low cycle fatigue damage. It shows that increasing the top tension can reduce the vortex-induced vibration amplitude of the riser, but increase the vibration frequency and stress value, which may lead to fatigue damage, so the tension should be optimized.
5. Conclusions

1. In this paper, the CFD-FEM bidirectional fluid-solid coupling method is used to establish the vortex-induced vibration model of the deepwater drilling riser under non-uniform ocean loading. After 60s of coupling calculation, the vortex-induced vibration of the riser reaches a stable vibration state.

2. The Marine non-uniform load makes the vortex-induced vibration amplitude near the upper third of the riser. The vorticity induced vibration has a strong three-dimensional characteristic, which is the dangerous area for the riser vortex-like vibration.

3. Under the action of non-uniform flow, the influence of velocity variation will interfere with the vortex-induced vibration of the riser, so that the amplitudes of the lateral and the flow direction are non-uniform to some extent, and the lateral vibration is more complicated than the flow direction vibration.

4. The large top tension reduces the lateral and flow direction vibration displacement of the riser and increases the frequency, and promotes the riser to enter a stable vibration state in a short time, which is beneficial to reduce the possibility of vortex-induced resonance.

5. The large top tension increases the stress level of the riser, and the high frequency vortex induced vibration may cause high stress and low cycle fatigue damage of the riser, and the tension needs to be optimized in combination with the actual.

References

[1] Wang, C.G., Wang, J.S., et al. (2011) 3D numerical simulation of Marine riser vortex-induced vibration. Journal of hydrodynamics research and progress, 26: 437-443.

[2] Zhou, J.L., Xu, L.B. (2018) Research progress of key technology of riser for deepwater drilling. China offshore oil and gas, 30: 135-143.

[3] Liu, Q.Y., Mao, L.J., Fu, Q., et al. (2015) Experimental study on the mechanism of the vortex-induced vibration of the drilling riser under shear flow. China offshore oil and gas, 27: 82-87, 92.

[4] Kaewunruen, S., Chiravatchradej, J., Chuicheepsakul, S. (2005) Nonlinear free vibrations of marine risers/pipes transport fluid. Ocean Engineering, 32: 417-440.

[5] Pereirap, S.D., Morooka, C.K., Champid, F. (2006) Dynamics of a vertical riser with a subsurface buoy. In: Proceedings of the Sixteenth International Offshore and Polar Engineering Conference. USA. pp.45-52.

[6] Cai, J., You, Y.X., Li, W., et al. (2010) The VIV characteristics of deep-sea risers with high aspect ratio in a uniform current profile. Chinese Journal of Hydrodynamics, 25: 50-58.

[7] Lin, L., Wang, Y.Y. (2013) Research on vortex-induced vibration in linearly sheared flow. Journal of Ship Mechanics, 17: 901-910.

[8] Liu, Q.Y., Mao, L.J., Zhou, S.W. (2014) Experimental study of the effect of drilling pipe on vortex-induced vibration of drilling risers. Journal of Vibro engineering, 16: 1842-1853.

[9] Zhu, H.J., Gao, Y., Zhou, T.M. (2018) Flow-induced vibration of a locally rough cylinder with
two symmetrical strips attached on its surface: Effect of the location and shape of strips. Applied Ocean Research, 16: 122-140.

[10] Fu, Q., Mao, L.J., Zhou, S.W., et al. (2016) The three-dimensional theoretical model for the vortex-induced vibration of deepwater drilling risers. Natural gas industry, 36: 106-114.

[11] Wang, G.R., Zeng, C., Mao, L.J., et al. (2018) Analysis on Dynamics and Configurations of Deepwater Drilling Riser Systems. Journal of Southwest Petroleum University (Science & Technology Edition), 40: 156-163.

[12] Sun, Y.Y., Chen, G.M. (2009) Fatigue induced by Marine riser wave in ultra-deepwater drilling system. Journal of petroleum, 30: 460-464.