Experimental investigation on vortex-induced vibration of variable diameter riser with uniform flow

Liping Feng, Peng Li*, Lihua Liu, Ziqian Zhong and Chuanzhen Wang

College of Architecture and Civil Engineering, Shandong University of Science and Technology, Qingdao, China

*Corresponding author: lipeng@sdust.edu.cn

Abstract. Diameter design of the riser is a very important link in offshore riser engineering, which will affect a series of parameter changes of the riser. In this paper, the riser is a variable-diameter riser with different cross-sections spliced by riser sections with diameters of 18, 25, and 30. In the wave-flow combined flume, dynamic response parameters such as strain-time history curve and root-mean-square of dimensionless strain were obtained by changing the outflow velocity and diameter of the riser, the effect of variable diameter on vortex-induced vibration of the riser was studied in detail. The results show that the vibration amplitude of the variable diameter riser varies with the axial position of the riser, but the frequency is dominated by the excitation of the thickest section riser; the variable diameter riser is always dominated by the first-order frequency in the outflow velocity range, and the relationship between the in-line and the cross-flow dominant frequency is always 2 times. With the increase of the flow velocity, the root mean square value of strain increases steadily.

1. Introduction

The great demand for crude oil of the world leads to oil and gas exploitation is no longer satisfied in shallow sea areas, offshore oil and gas exploration has gradually shifted to deep sea areas, which has higher requirements for the safety of offshore risers. Marine risers, which are connected to offshore platforms from the top and connected to seabed wellheads from the bottom, play an extremely important role in deep-sea oil systems, so it is very important to protect the stability of marine risers in complex environments. With the increasing depth of marine riser, higher requirements are put forward for the parameters of all aspects of marine riser. Among them, there are many researches on the influence of riser diameter on vortex-induced vibration (VIV), which are specifically discussed by changing different aspect ratio ($L/D$) in the test.

For example, Gao et al. [1] studied vortex-induced vibration of risers by changing the boundary conditions and aspect ratio, and found that the different aspect ratios would have a great influence on the displacement and modal changes of riser. Goncalves et al. [2] studied the dynamic response characteristics of risers with eight different aspect ratios, and concluded that the amplitude decreased with the decrease of aspect ratio. At present, studies on risers are mostly focused on equal-diameter risers. Ma Zhe et al. [3] found that the vortex-induced vibration of cylinder with variable cross-section can be effectively suppressed by changing the structure form. Hong et al. [4] conducted VIV tests on towed risers with uniform cross section risers and non-uniform cross section risers, and found that the
response of uniform cross section risers was dominated by single frequency, while the response of non-uniform cross section risers was more likely to be controlled by many frequency components. In terms of numerical simulation, Tang et al. [5] carried out finite element analysis on variable diameter piles, indicating that, in extreme wave conditions, the displacement and stress reduction of variable diameter piles are greater than 20% compared with that of full-length piles, no matter in static calculation or dynamic calculation. Li et al. [6] found that the variable section riser system was significantly different from the constant section riser system in terms of response amplitude, vibration frequency and lock-in region.

Due to the different pressure generated by different water depths, in order to improve the anti-extrusion performance of marine risers, increase its own strength and make the anti-vibration performance of each position of the riser more consistent, the optimal diameter is usually selected when designing the riser. However, it will cause a great waste of materials and increase the engineering cost output. Therefore, when designing the riser, the section diameter of the riser can be changed according to the water depth and water pressure, which not only saves the cost of riser, but also greatly reduces the weight of the riser and the load of the drilling platform. However, the influence of the variable cross-section design on the overall dynamic response and dynamic characteristics of the riser is still unknown. Therefore, based on physical model tests, this paper changes three riser diameters along the axial height of the riser to explore the dynamic response and dynamic characteristics of the riser due to the change in cross-section diameter.

2. Experimental details
The experiment was carried out in the wave-current combined water flume in the Engineering Hydrodynamics Laboratory of Ocean University of China. The water flume is made of glass on both sides and steel plate at the bottom, which can be used to fix the test device and meet the requirements of the external environment of the test. The experimental device applies top tension through the top tension system. In order to increase the stiffness of the upper fixing structure of the riser, the aluminum alloy upper fixing plate is connected with the guide plate through the high-strength force transmission screw. The upper part of the riser is connected with the external digital display tensiometer through the universal joint. The universal joint can ensure that both ends of the model are not subjected to the action of bending moment while torsion movement cannot occur. The tensiometer display is placed on the external beam of the bracket, so that it can accurately apply force. The lower part is connected with the lower fixed plate of aluminum alloy through universal joint, so that the riser can rotate in the direction of two degrees of freedom in the cross-flow (CF) and in-line (IL) directions.

The model material of the riser is organic glass (PMMA). Considering the influence of stress concentration, when the outflow flows through the riser, it contacts the middle part of the riser at the free surface of the flow. Therefore, in the design model, the riser is divided into 5 sections. The diameter of the middle section is the largest, and the diameters of the two sides of the riser gradually decrease. The upper and lower sections are arranged symmetrically about the middle of the riser to reduce stress concentration. The diameter D₃ of both ends of the riser is 18mm, the diameter D₂ of the transition section is 25mm, and the diameter D₁ of the middle section is 30mm. The riser model is shown in Fig. 2.
Figure 1. Schematic diagram of the test device.

Figure 2. Riser layout diagram (a) Test bracket diagram; (b) local view of the riser; (c) Schematic diagram of riser model.

The riser was adopted a standing posture, and the lower 0.8m (40%) is in a uniform flow field. The measurement points are arranged as shown in Fig. 2. Three groups of measuring points were arranged, each group of measuring points is located in the middle of the riser section, and two groups of strain gauges were arranged at an interval of 90° for each measuring point, with two groups of strain gauges in each group, along CF and IL directions. The strain gauge is composed of a half bridge measuring system to measure the dynamic strain in CF and IL directions respectively. The outflow velocity is \( U = 0.1 \text{m/s} - 0.7 \text{m/s} \), the increment is \( \delta_v = 0.05 - 0.1 \text{m/s} \), with 11 stages.
3. Results and discussions

3.1. Strain analysis of riser varying with velocity variation

Fig. 3 shows the variation of the root-mean-square (RMS) strain of the three sections of the riser with the flow velocity. With the increase of the external flow velocity, the three riser sections have the same changing trend, and both the initial branch and the upper branch appear. The riser has different amplitude responses along the axial position of the model. From the end to the middle of the riser, the strain response amplitude increases continuously. Since section a of the riser is in direct contact with the water flow, the impact force of the water flow is the largest, so the strain amplitude of section c of the riser is the smallest under the same flow velocity, followed by section b, and section a is the largest, especially after the external flow velocity of 0.3m/s. At the same time, after $U \geq 0.3$ m/s, the outflow velocity increases, and the lift and drag resistance of the riser increases, resulting in a significant change in the RMS strain value of the riser, and the increase in amplitude increases. When $U \geq 0.5$ m/s, the change trend of the three riser sections is the same, the strain increases linearly, and the slope is similar. It can be seen that the same riser produces different strain amplitudes due to different model axial positions, but the change law and slope approach the same, indicating that the dynamic characteristics of the same riser at different positions are the same and will not change due to changes in axial position and diameter.

![Figure 3. RMS strain diagram in the CF (left) and IL (right) directions of three-section diameter riser with flow velocity.](image)

3.2. Frequency analysis of riser with velocity variation

Since the strain of the riser begins to change significantly after the external flow velocity of 0.3m/s, in the following analysis, the flow velocities after 0.3m/s are taken as the characteristic flow velocities for analysis. Understanding the frequency changes of each riser section at different flow velocities is of great research value for analyzing variable diameter risers. Therefore, Figs. 4 and 5 show the vibration power spectral density curves in the CF and IL directions under the characteristic flow velocities of the three riser sections. The calculation formula $f_i = S_i / D$ for the vortex shedding frequency of the riser shows that the vortex shedding frequency of the riser is affected by the diameter, that is, the vortex shedding frequencies of the three riser sections of the variable-diameter riser are different from each other. In other words, the variable-diameter riser is coupled to vibrate at three different vibration frequencies, but because the stiffness and mass of the riser of section an are the largest, and the vertical swing and swinging are increased, the riser vibration is dominated by the excitation of the thicker section. As shown by the red arrow in the figure, each riser section only has a slight difference in the peak power spectrum, section a of the riser has the largest peak, but the frequencies are completely the same. This phenomenon is consistent with the conclusion drawn by Hong et al. [7]. At the same time, whether it is
In order to further understand the dynamic response and dynamic characteristics of three sections of the riser, Fig. 6 compares the coupled vibration response diagrams of the three sections of the riser in the CF and IL directions as a function of outflow velocity. In each of the sub-diagrams, the x-axis represents
the strain in the IL direction and the y-axis represents the strain in the CF direction of the riser. It can be seen from the diagram that the evolution law of coupling vibration of the trajectory of three sections of the riser segments is consistent. As Zhuang et al. [8] studied the riser trajectory, the vibration trajectory of the riser is in the shape of "crescent" or "8" shape due to the frequency ratio of IL to CF direction always being 2 times in the flow velocity range. At high velocity, the riser always maintains a large and stable vibration in the IL direction. Under the excitation of the outflow velocity, the strong nonlinear coupling between the CF and IL directions of the riser leads to an "8"-shaped trajectory in the riser. And it’s found that the coupling trajectories of the three riser sections are similar, but the larger diameter riser section shows a larger trajectory range.

Figure 6. Coupled vibration trajectory diagram of three riser sections with flow velocity changes.

4. Conclusion
In this experiment, the dynamic characteristics and dynamic response of the variable diameter riser structure under different flow velocities conditions were studied by changing the size and shape of the riser, and a summary analysis was carried out according to different test conditions to provide a certain test basis for future riser design.

It is found that the axial position of the variable-diameter riser is different, and the vibration amplitude is obviously different, but the change law and the coupling trajectory are close to the same. The riser is coupled to vibrate at three different vibration frequencies, but the vibration is dominated by the excitation of the thicker section. That is, the vibration frequency of the thickest cross-section riser section occupies the dominant position of the entire riser. It can be seen that the dynamic characteristics of different axial positions of the variable-diameter riser are the same, and the cross-sectional diameter will not change. Therefore, in actual engineering applications, risers of different diameters can be arranged according to changes in the external environment and water depth, which saves engineering costs and reduces the weight of the risers and the load of the drilling platform.

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