

Load Analysis of Connectors for Floating Structures at Sea

Xinyue Zhang, Jin Wang *, Lijun Li, Shouyi Sun, Zaiqiang Wang

School of Mechanical and Automotive Engineering, Qingdao University of Technology, 777 East Jialingjiang Road, Qingdao Economic and Technological Development District, Qingdao 266000, China

* Corresponding author: Jin Wang (Email: wangjin@qut.edu.cn)

Abstract: Taking four modules of offshore floating structure connectors as the research object, the time domain analysis using the hydrodynamic calculation software AQWA was used to obtain the load amplitude of the connectors under different environmental effects. Based on the three-dimensional potential flow theory of hydrodynamics, the models of four modules of offshore floating structures in mooring state and three groups of connectors in the middle are established in AQWA, and the influence of environmental action changes on connectors and the time history curve of the load on connectors are simulated and calculated in five different sea states and seven different wave incidence angle marine environments. The calculation results show that the floating structure can be detached when the sea state is level 6, and the floating structure should be tried to avoid the wave angle of 45° when working, the longitudinal load amplitude of the connector is greater than the transverse and vertical load amplitude, and the load fluctuations of the connector in different directions are more balanced.

Keywords: Offshore Floating Structures; Connector Load; AQWA; Different Sea States; Different Wave Angles.

1. Introduction

Countries around the world pay more and more attention to the development and utilization of marine resources. China's sea area is broad and rich in fishery and mineral resources. How to efficiently and safely develop and utilize deep-sea resources and energy requires not only extraordinary courage, but also excellent technology and supporting equipment. As a tool for human exploration of marine oil resources and production, the development of offshore platforms has attracted much attention. Due to population growth and urban development, human beings are facing the problem of land shortage. In order to solve this problem, engineers and designers put forward the concept of floating structures at sea. Compared with the traditional land reclamation technology, offshore floating structure is a unique alternative method to build land space on the seabed, which provides production and living facilities for offshore drilling, transportation, observation, navigation, construction and other activities[1]. Such as floating airports[2], oil and gas development and storage facilities, military bases at sea, floating stage at sea[3], floating pastures at sea[4], etc.

Linjian Wu et al.[8]calculated the wave load on the mobile offshore base (MOB) structure by using the modified Morison equation instead of the potential flow theory. The results show that the increase of the wave incident angle will reduce the dynamic constraint force of the connector in the x direction, while in the y and z directions, it increases first and then decreases. The dynamic restraint force increases with the increase of sea conditions, and increases linearly with the increase of connector stiffness. Weiqin Liu et al.[9]proposed an FMRC (Flexible Modulus Rigid Connector) HEP model, and studied its hydrodynamic response through numerical simulation and model experiment. The numerical results and experimental results in frequency domain and time domain were obtained. The results show that the experimental results are consistent with the numerical results. Based on the RMFC method, Chen et al.[10]established the frequency domain

model of the hydrodynamic structure of the multi-module floating system. The three-module floating body was connected in series by flexible connectors, and different connection stiffness was designed. Riggs et al.[11]calculated the motion response of a 16-module very large floating body in regular waves using the RMFC model based on the three-dimensional hydroelastic theory. The research shows that the hydrodynamic interaction between the modules is relatively small, and the maximum load of the connector appears under the action of oblique waves.

The above literature has very important theoretical and practical significance for the analysis of connector load of multi-module floating structure. In this paper, the AQWA calculation module in ANSYS Workbench software is used for numerical simulation. AQWA is mainly used to solve the problems of motion response, mooring positioning, offshore installation, ship navigation and wave load transfer of various marine structures under environmental loads [9]. It mainly includes nine modules. Among them, the AQWA-Line module can be used to deal with the shallow water effect, and can calculate the wave force around the floating structure at any water depth. At the same time, the added mass and added damping of the floating structure and the first and second order wave forces of the near-field solution can be obtained. The AQWA-Librium module is used to determine the equilibrium position of the floating structure by comprehensively considering the external environmental loads (wind, wave, current) and the interaction force generated by the hinged connection between the floating structures. The AQWA-Naut module is used for time domain simulation to calculate the connector load amplitude and load time history of floating structure motion transmission under different working conditions and different wave incident angles.

2. Theory and Methodology

The complexity of the marine environment is one of the main difficulties to be overcome in hydrodynamic analysis. In

order to better simulate the impact of the marine environment on floating structures, it is often necessary to carry out reasonable simplification and use appropriate mathematical theories and calculation methods for modeling and analysis in order to reduce computational complexity and improve computational efficiency. The three-dimensional potential flow theory analysis method is used to calculate the multi-module floating structure connection system, which is simple and convenient, and can meet the engineering accuracy requirements.

2.1. Three-dimensional Potential Flow Theory

The potential flow theory assumes that the liquid is an incompressible ideal fluid without rotation, and the wave is small amplitude.

Satisfy the velocity potential energy control equation (Laplace equation):

$$\nabla^2 \phi = 0 (\vec{\nabla} = \nabla \phi) \quad (1)$$

Boundary conditions:

$$(\nabla^2 \phi - \frac{\partial}{\partial v_s}) \vec{n} = 0 \quad (2)$$

Seabed boundary conditions

2.2. Wave Spectrum

The wind and waves on the sea surface are large and small, and unevenly fluctuate around the average sleep, becoming irregular waves. In the field of ship and ocean engineering, the spectral density analysis method of irregular waves is widely used. The area under the spectral density curve is a measure of the total energy of the wave in the unit wave surface. It is the main index to measure the severity of the sea state. The relationship with the mean square error is as follows:

$$\sigma^2 = \int_0^\infty S(\omega) d\omega \quad (3)$$

In the formula: $S(\omega)$ for the spectral density (m²s / rad); ω is a circular frequency (rad / s).

There are many kinds of wave spectrum. The common wave spectrum includes Neumann spectrum, Pierson-Moskowitz spectrum (P-M spectrum), ISSC spectrum, JONSWAP spectrum and Bretschneider spectrum. In this numerical simulation, the wave adopts JONSWAP spectrum.

2.3. Wind and Flow Loads

The wind is a continuous flow of large-scale air at a certain speed in the horizontal or vertical direction. It is an important natural phenomenon in the marine environment. The deck, some columns and connectors of the floating structure are above the water. Therefore, the load caused by the wind must be considered when analyzing the connector load of the floating structure. The wind load is generally calculated by specifying the wind coefficient and inputting the wind speed in the calculation model.

Ocean current is a continuous flow of air in a wide range in a horizontal or vertical direction at a certain speed. It is an important natural phenomenon in the marine environment. The columns, lower pontoon and struts of floating structures are underwater parts. Therefore, when analyzing the load of floating structure connectors, the load caused by wind current must be considered. The current load is generally calculated by specifying the flow force coefficient and inputting the flow rate in the calculation model.

3. Introduction of Offshore Floating Structures

3.1. Geometric Model

The model consists of four floating modules and six connectors. According to API RP 2SK 'Design and Analysis Specification for Floating Structure Positioning System' and CCS2020 'Classification Specification for Offshore Mobile Platforms', each floating structure module consists of one upper deck, six columns, two lower pontoon and three struts between the lower pontoon and the lower pontoon. All floating structures are formed by steel plates with a thickness of 20 mm. as shown in Fig.1.

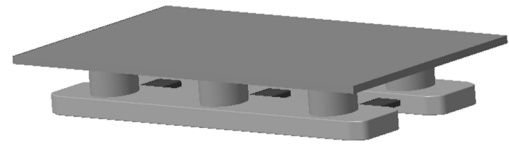


Figure 1. Geometric model of a single-module structure

3.2. Coordinate System

There are two coordinate systems in AQWA. One is the global coordinate system FRA. For example, the large black coordinate axis in the figure is the global coordinate system of the hydrodynamic model of the floating structure, and the combined action angle of wind, wave and current refers to the coordinate axis. The other is the local coordinate system LSA. For example, the local coordinate axis with small blue and red is the local coordinate system at the connection point between the modules of each floating structure. The red local coordinate axis releases the degree of freedom in this direction. On the contrary, the blue local coordinate axis constrains the degree of freedom in this direction. The connection form between floating structures studied in this paper is hinged connection. In AQWA software, the hinged connection between floating structure modules is simulated by releasing the constraint around the y-axis at the connection point and constraining other degrees of freedom.

The origin of the global coordinate is located at the intersection of the transverse section, the middle longitudinal section and the waterline surface in the second module on the left. The two modules are connected by two connectors. The connectors are connected to the deck of each floating structure, and the underwater part is not connected to each other. In this simulation, a total of four modules are calculated. The spacing of the modules is 20 meters. There are six connectors in total, which are divided into three groups, C1-C3. The connectors are arranged on the deck of the floating structure. The transverse position of the two connectors is only allowed to rotate around the x-axis in the local coordinate system, so it is only necessary to specify the y-direction (transverse) rotation stiffness of 1E10N / m.

3.3. Load Environment

Considering the load characteristics of marine floating structure connectors under the combined action of wind, wave and current, in order to obtain the maximum load of connectors, the wind and current coefficients in the sea area are calculated with reference to the specification API RP 2SK. The wind and current loads are taken into account in the

influencing factors of the motion response of floating structures, and the actual sea conditions are simulated more realistically. It is assumed that the directions of wind, wave and current are in the same direction, and the angle between the propagation direction of wind, wave and current and the counterclockwise direction of x-axis is calculated from the angle of x-axis in the global coordinate axis. The wave load is random load, which is related to different sea conditions. The wind and current are steady wind with wind speed of 18m / s and uniform flow with velocity of 0.3m / s respectively.

3.4. Introduction of Model Mooring System

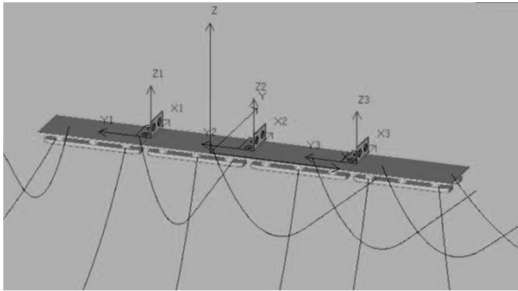


Figure 2. Catenary mooring schematic diagram

Since the four-module offshore floating structure works in a 400 m deep ocean, it will encounter a complex and changeable harsh marine environment, so the mooring system of the floating structure is essential. The mooring system is composed of 12 catenary mooring cables arranged in a radial arrangement. Fig.2 is a schematic diagram of the catenary mooring scheme for offshore floating structures. The length of each mooring line is 1120 m. The main component of the anchor chain is a chain ring. The chain ring is divided into a chain ring and a non-chain ring. The strength of the chain ring with the same chain diameter is about 20 % higher than that of the non-chain ring. As shown in Fig.2, the yellow section of the upper end of the mooring line is an anchor chain, which provides the initial tension of the whole mooring system. The black section of the lower end of the mooring line is a steel cable, which is connected with the fixed anchor point on the seabed, providing enough lying area to prevent the anchor end from pulling up.

4. Connector Load Calculation

The numerical simulation uses the hydrodynamic software AQWA to simulate the environmental loads under different sea conditions and different wave angles by using the three-dimensional potential flow theory. Because the model size is relatively large, the software analysis takes a long time to reach a stable calculation, so the total time is set to 7200 s, and the time step is 0.1 s. In the frequency calculation, each module is set as a rigid body.

4.1. The Influence of Different Sea Conditions on Connector Load

Different sea conditions correspond to different characteristic wave heights and spectral peak periods. The short-term forecast values of the floating structure module motion and the short-term forecast values of the connector load will be affected by sea conditions. In order to study the influence of different sea conditions on the connector load, five sea conditions between the 4th and 8th sea conditions in the North Pacific were selected to calculate the short-term prediction values of the connector load under different sea

conditions. Different sea state parameters are shown in Table 1.

Table 1. Wave height and spectral peak period of different sea states

Sea state	Significant wave height	Wave spectrum peak period
SS4	1.88 m	8.8 s
SS5	3.25 m	9.7 s
SS6	5 m	13.8 s
SS7	7.5 m	15 s
SS8	11.5 m	18 s

The load amplitude of the C1-C3 connector in three directions under all levels of sea conditions is shown in Figure 3.

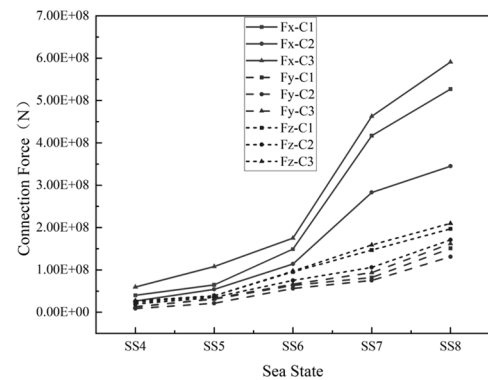


Figure 3. The load amplitude of the connector in three directions under different sea conditions

The statistical line chart of the load amplitude in three directions of the C1-C3 connector under different sea conditions:

(1) It can be seen from the diagram that with the continuous increase of the sea state level, the load amplitude of the connector in three directions is also increasing. When the sea state increases from level 5 to level 6, the increase of the load value of the connector becomes larger, and the load of the connector increases sharply at level 7.

(2) The law of the load amplitude in the longitudinal, transverse and vertical directions of the connector is $C3 > C1 > C2$. The force of the connector outside the two groups of the overall model is greater than that of the connector in the middle group.

From the above diagram, it can be seen that the maximum load of the connector increases with the increase of the sea state. The load of the connector increases sharply under the 7-sea state, so the maximum load of the connector increases with the increase of the sea state.

4.2. The Influence of Different Environmental Action Angles on the Connector Load

Through the above simulation calculation, the connector load amplitude is huge after the 6-level sea condition. Therefore, in order to ensure the safety of the connector and the offshore floating structure, the connector load is calculated to be affected by different environmental angles under the 6-level sea condition.

Because the floating structure model is symmetrical about the OXZ plane, the X-axis symmetrical structure in the

AQWA-Line module simulates the wave direction range of 0° - 90° . Therefore, in order to reduce the calculation load analysis conditions, when studying the influence of different wave incident angles on the connector, seven wave incident angles were selected to study and analyze the connector load. Each interval was 15° , and the connector load was calculated once. The wave frequency was 60, from 0.1 rad / s to 1.35 rad / s.

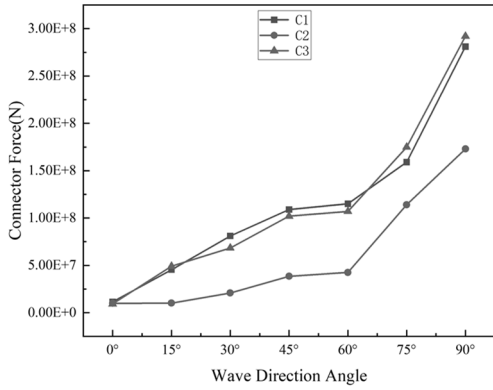


Figure 4. Amplitude of connector longitudinal load at different wave angles

The statistical line chart of longitudinal load amplitude of C1-C3 connector under different wind, wave and current angles:

(1) It can be seen from the figure that with the increase of the action angle, the load of the three groups of connectors increases slowly. After the incident angle of the wave exceeds 60° , the load value of the connector increases obviously. When the angle of wind, wave and current is 0° , that is, the load of the connector is the smallest when facing the wave, and when the angle of wind, wave and current is 90° , that is, the load of the connector is the largest when the transverse wave.

(2) When the angle of wind, wave and current is 0° , the connector load of C3 group is less than that of C1 group and C2 group. Under the action of wind, wave and current load, due to the shielding effect between the floating structure modules, the force of the connector in the x direction becomes smaller and smaller with the increase of distance.

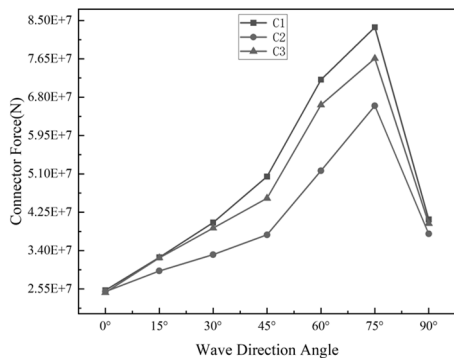


Figure 5. Amplitude of connector transverse load at different wave angles

The statistical line chart of transverse load amplitude of C1-C3 connectors at different wave angles:

(1) It can be seen from the figure that with the increase of the angle of action, the load of the three groups of connectors is increasing. When the angle reaches a certain angle, the load value will decrease again. When the incident angle exceeds 45° , the load value of the connector increases obviously, indicating that the force of the connector becomes more

complicated when the direction of the environmental load is side waves. When the angle of wind, wave and current is 75° , the load of the connector is the largest, and the angle of wind, wave and current is 0° , that is, the load of the connector is the smallest when facing the wave.

(2) At 0° and 90° wind, wave and current angles, the load values in the y direction of each group of connectors are similar, indicating that the relative rolling motion of each floating body module is small under the action of head waves and cross waves.

4.3. Connector Load Time History

At the angle of 75° wind, wave and current, the load history curves of C3 group connectors in longitudinal, transverse and vertical directions with time are shown. It can be seen from the figure that the force load fluctuation of C3 group connectors in three directions is relatively symmetrical. This may indicate that the environmental forces acting on the C3 connector in the longitudinal, transverse and vertical directions are relatively balanced and there is no obvious bias under the marine environmental conditions. This helps to maintain the stability and balance of the floating structure and reduce unnecessary structural dynamic response. Through the polishing and analysis of the load history curve of the connector, we can better understand the stress of the connector in different directions, and provide valuable reference and basis for further design and optimization.

5. Conclusion

Based on the three-dimensional potential flow theory, the time domain method is used to numerically simulate the multi-module deep-water floating structure, and the load amplitude of the hinged connector is studied. The results show that:

(1) The load amplitude of the connector increases with the increase of sea state. The load of the connector increases sharply in the 7th sea state. After the 7th sea state, the longitudinal load amplitude of the connector is three times that of the transverse load amplitude and the vertical load amplitude. Therefore, it should be ensured that the connector can be disconnected in the 6th sea state to ensure the strength safety of the connector and the offshore floating structure.

(2) Among the seven environmental action angles in the range of 0° - 90° , in the overall case, when the action angle exceeds 45° , the load value of the connector increases sharply. The load of the connector is the largest at the action angle of 75° , and the load of the connector is the smallest at the action angle of 0° . Therefore, it should be ensured that the floating structure should avoid the 45° wave angle when working.

References

- [1] JIANG D, TAN K H, WANG C M, et al. Research and development in connector systems for very floating structures[J]. Ocean Engineering, 2021, 232, 109150.
- [2] Wang C M, Tay Z Y. Very large floating structures: applications, research and development[J]. Procedia Engineering, 2011, 14: 62-72.
- [3] Koh H S, Lim Y B, Seow T H, et al. The Floating Performance Stage @ Marina Bay, Singapore: New Possibilities for Space Creation[C]//International Conference on Offshore Mechanics and Arctic Engineering. 2008, 48203: 755-763.
- [4] Laurence S, Roels O A. Marine Pastures: A by-product of large (100 Megawatt or larger) floating ocean-thermal power plants

- [J]. Final Report Lamont-Doherty Geological Observatory, 1976.
- [5] Sueoka H , Sato C .Phase II research of mega-float[C]// International offshore and polar engineering conference.2000.
- [6] McAllister K R. Mobile offshore bases--an overview of recent research[J]. Journal of Marine Science & Technology, 1997, 2(3):173-181.DOI:10.1007/BF02489808.
- [7] Paulling J R, Tyagi S. Multi-module floating ocean structures [J]. Marine Structures, 1993, 6(2-3):187-205.DOI: 10. 1016/0951-8339(93)90019-Y.
- [8] WU L, WANG Y, XIAO Z, et al. Hydrodynamic response for flexible connectors of mobile offshore base at rough sea states [J]. Petroleum Exploration & Development, 2016, 43(6): 1089-1096.
- [9] WLA B , XG A , GZ A , et al. Experiment and numerical investigation on structural response of a FMRC hexagon enclosed platform in waves[J]. Ocean Engineering, 233.
- [10] Chen M, Ouyang M, Guo H, et al. A Coupled Hydrodynamic–Structural Model for Flexible Interconnected Multiple Floating Bodies[J]. Journal of Marine Science and Engineering, 2023, 11(4): 813.
- [11] Riggs H , Ertekin R .Characteristics of the Wave Response of Mobile Offshore Bases[J]. 1999.