Comparative Analysis and Differential Study on Dynamic Response of Tension Type Mooring and Catenary Mooring System

Jiangfeng Zhu¹, Yuguang Cao¹ and Lei Zhang¹

¹ Engineering Mechanics Department, College of Pipeline and Civil Engineering, China University of Petroleum (East China)
E-mail: b18060002@s.upc.edu.cn

Abstract. Mooring system is an important factor affecting the safety and motion law of floating body. It is very important to study the hydrodynamic characteristics of different mooring methods for offshore safety engineering and stability analysis of mooring system. Taking oc4 as a floating body hydrodynamic model and considering the combined action of wind, wave and current, the hydrodynamic characteristics and system stability of taut and catenary mooring mode are compared and analyzed respectively. In addition, the differences and variation rules of dynamic response of floating body under different mooring conditions are explored and summarized. Combined with the time-domain analysis theory and simulation results, the coupled motion equations of taut and catenary mooring system are improved, and the corresponding relationship between slow drift motion and different mooring modes is summarized. It provides an important theoretical basis and support for the research of time domain variation law of mooring system and marine safety control.

1. Introduction

Mooring system is widely used in ocean engineering technology. It is an important factor affecting the overall safety, stability and reliability of floating structures. At present, there is a lack of research on the difference of attitude stability and motion law of floating body with different mooring methods and mooring materials. Because of the difference of material and structure, it also shows different advantages and defects in mechanical properties. At present, the research on mooring system mostly focuses on the structural design and the stability analysis of mooring taut extreme value and maximum response position, while the research on the motion process and time domain law of mooring floating body is less. L Zhang[1-2] designed a new design method based on semi-submersible wind turbine foundation mooring system. The dynamic method was used to analyze the mooring parameters, which provided reference for the design of semi-submersible floating wind turbine mooring system, but did not analyze the overall dynamic characteristics of mooring lines. H.C. Kim[3-6] compared the motion response and mooring chain taut of OC4 and floating wind turbine foundations, and obtained that OC4 has better dynamic characteristics, but did not explain the influence of different mooring lines on system stability. Fan H[7] carried out the design and comparative analysis of two mooring systems based on OC4, and obtained the optimal design method, but did not study the motion laws of the two mooring systems. In this paper, based on the traditional analysis idea, the OC4 floating body of semi-submersible floating fan foundation is taken as the model, and the characteristics of time-domain motion stability and taut change of the floating body under different mooring modes are emphatically
considered, and the stability control and mechanical change law of different mooring methods and materials on floating structure control are explored.

2. Modeling and analysis of semi submersible OC4 Foundation

According to the requirements of determining environmental load parameters in S4 operation area and water depth in South China Sea, the 5MW floating fan model and OC4 semi-submersible floating fan foundation published by NREL were selected for model test and analysis. The foundation is one of the most widely used offshore wind turbines[8]. Table 1 shows the main structural parameters of the fan platform. The draft of OC4 is 20m and the weight is $1.3473 \times 10^7$ kg. The foundation structure is simple, the center of gravity is low, and the stability is good[9].

| Project                        | Parameters                             |
|--------------------------------|----------------------------------------|
| Capacity (MV)                  | 5                                      |
| Type                           | Upwind, Three blade                    |
| Rotor / Hub diameter (m)       | 126/3                                  |
| Cut in / Rated / Cut out wind speed (m·s$^{-1}$) | 3/11.4/25                             |
| Total weight of upper part of fan tower (kg) | 847460                                |
| Hub height (m)                 | 90                                     |
| Center of gravity of overall structure (m) | (0.1, 0, 17.9)                       |

The operating sea area of the wind turbine is S4 sea area of South China Sea, and the operating water depth is 200m. The rated wind speed of 5MW wind turbine is selected as the sea state wind speed. In order to ensure the safety of the structure, the extreme sea state with a return period of 10.6m, a period of 15.8s, a wind speed of 58m/s, and a sea water velocity of 2.3m/s are selected. The JONSWAP spectrum is used for the wave spectrum, and the NPD spectrum is selected for the wind spectrum. The load direction is $0^\circ$ and the wind wave current is in the same direction along the negative direction of X-axis [10].

![Figure 1. Hydrodynamic model of OC4](image)

The finite element software ANSYS and the hydrodynamic analysis software Aqwa are used to establish the hydrodynamic model of the foundation buoy and strut, as shown in figure 1. Among them, the buoy is a large-scale component with the characteristic scale and wavelength ratio greater than 0.2, and the panel model is established, mainly using the three-dimensional potential flow theory to calculate the wave load; the ratio of the characteristic length to wavelength of the strut is less than 0.2, so it is a small-scale component. The Morrison bar element model is established and solved by Morrison formula, which can meet the engineering requirements [11].

Set the direction of wind, wave and current load as $0^\circ$. The wave period is 0.1~2.4rad/s and the interval is 0.1rad/s. considering the symmetry of the foundation, the wave direction is $0^\circ$ to $180^\circ$ and...
the interval is 30°. The natural periods of OC4 in heave, roll and pitch are obtained and compared with the experimental results[12]. As shown in table 2, the errors are less than 3%, which verifies the accuracy of the model.

| Table 2. Inherent period of OC4 |
|-------------------------------|
| Inherent period(s) | Heave | Roll | Pitch |
| Simulation          | 17.02 | 26.54 | 26.54 |
| Test               | 17.5  | 26.96 | 26.8  |
| Margin             | 2.7%  | 1.6%  | 1.0%  |

3. Comparative analysis of dynamic response of different mooring modes and materials
The commonly used mooring methods at sea include taut mooring and catenary mooring. Taut mooring achieves the fixed effect of offshore mooring through cable pre-taut, while catenary mooring realizes the function of stable positioning of floating body by the gravity of the cable itself. Considering the difference of structure types between taut mooring and catenary mooring, OC4 hydrodynamic response motion stability law and mooring taut change are also different in time domain analysis.

3.1. Mooring theory analysis
Time domain coupled motion equation of floating body considering mooring system.

\[ F_i(t) + F_m(t) = \sum_{j=1}^{6} \left( M_{ij} + \mu_{ij}(x) \right) \ddot{x}_j(t) + \int_{-\infty}^{\infty} K_{ij}(t - \tau) x_j(\tau) d\tau + C_{ij} x_j(t), (i = 1, ..., 6) \]  

Among them, the \( F_i(t) \) environmental force acting on the floating body is mainly affected by the wind, wave, current and sea state, and the \( F_m(t) \) mooring force is related to the mooring mode.

As shown in Figure 2, (a) and (b) respectively show the time-domain variation rules of taut mooring and catenary mooring. Under the action of wind, wave and current environment, the position response and taut type change range of the mooring floating body are small, and the whole system is in dynamic equilibrium state. Figure 2 (a) in the time domain analysis of a taut mooring floating body, the wave current force \( F_m(t) \) is a harmonic input, and the taut mooring force \( F_m(t) \) is polarized up and down with the floating body, and its amplitude is between \( F_m1 \) and \( F_m2 \). Because the floating body is close to the motion form of harmonic sine wave, the equation is satisfied when it reaches dynamic equilibrium.

\[ F_i \sin \theta = -F_m (1 + b \sin \varphi) \]  

In the formula, \( \sin \theta \) and \( 1 + b \sin \varphi \) mean that the environmental load and taut of the taut mooring structure meet the sinusoidal variation law.

\[ F_i \sin \theta = -F_m (1 + b \sin \varphi(t)) + M_a(t) \]  

In the formula, the taut \( F_m \) of catenary mooring is not only affected by environmental forces, but also under the action of slow floating of floating body, the cable suspension angle decreases and the mooring taut increases. Compared with the taut mooring, the time slow drift taut factor \( c(t) \) is increased.
When the catenary mooring reaches dynamic equilibrium, the influence of floating body acceleration $a(t)$ can be ignored. At this time, the change of mooring taut $F_m$ in time domain also presents a sine wave law.

### 3.2. Comparative analysis of hydrodynamic forces of different mooring modes

According to IEC 61400-1:2005, the load limit depends on the maximum 10min average wind speed and maximum 3S wind speed in 50-year return period, and the ultimate wind speed is also related to the safety of the fan, and is one of the key indexes for the selection of units and economic evaluation in the development of wind power projects. The paper analyzes and studies three common mooring combinations of taut type steel cable, taut type polyester cable and catenary type steel cable. In order to further ensure the safety of the structure, the 100 year return period extreme sea condition in the South China Sea is selected when the self storage sea condition is selected, and the operating sea condition is determined according to the working wind speed of 5MW wind turbine published by NREL. The specific environmental parameters are shown in table 3.

| Sea state | Water depth(m) | Wave spectrum | Wave height(m) | Cycle(s) | Wind spectrum | wind speed(m·s⁻¹) | ocean current(m·s⁻¹) |
|-----------|----------------|---------------|----------------|----------|---------------|-----------------|-------------------|
| Normal    | 200            | JONSWAP       | 5.49           | 11.3     | NPD           | 11.4            | 0.39              |
| Extreme   |                |               | 10.6           | 15.8     |               | 56.3            | 2.3               |

In order to ensure the reliability of simulation test results, the minimum breaking forces of steel cable and polyester cable are set to be the same, and the parameters of taut cable and catenary cable are the same except for the length. According to the designed taut mooring scheme, considering the combined action of wind, wave and current, the time-domain response analysis of the three mooring forms is carried out according to the same sea state standard, and the suitable response curve and taut variation law of the mooring floating body are obtained.
Figure 3 and figure 4 are the time domain response curves of the three degrees of freedom of the taut cable and the catenary cable respectively, in which the surge response results are quite different. Figure 3 the motion law of the taut mooring in the three degrees of freedom directions is similar. The hydrodynamic response presents a relatively regular low amplitude harmonic motion with an amplitude of ±2.0m. The motion response of the floating body is relatively stable because the taut steel cable can provide relatively stable mooring in the hydrodynamic analysis process. In the time domain analysis, the motion amplitude of OC4 is mainly affected by the impact of 0° harmonic current. Large amplitude of surge motion. Figure 4 the hydrodynamic force of OC4 in catenary mooring is affected by both the 0°regular harmonic wave and the flexible elongation of mooring line, and the amplitude of motion response varies greatly.

Figure 5. Stress diagram of two mooring modes

In terms of the position response of pitch, roll and yaw, the rolling amplitude of the two mooring modes is relatively large and close to the sinusoidal variation rule. The maximum rolling amplitude of taut mooring is -8.82° which meets the standard ±15° range; the maximum rolling amplitude of catenary mooring is 1.53° which is more stable and stable than taut mooring mode, as shown in figure 5 Large horizontal forces $F_{m1}$ and $F_{m1-2}$ are generated at the fairlead, which form torque with $F_{m1}$ on the floating body, and easy to produce roll deflection in OY direction.
Figures 6 and 7 show the time-domain variation curves of the taut of the two mooring modes. It can be seen from Figure 6 that the taut of the three steel cables of the taut mooring mode presents a sinusoidal variation law, and the minimum taut is close to 0N, which is in line with the law that the mooring lines only provide tensile stress. When the floating body reaches dynamic equilibrium, the taut of different mooring lines and the environmental force shall meet the following requirements.

\[ F_{m1}(t)\cos\alpha_1 + F_{m2}(t)\cos\alpha_2 + F_{m3}(t)\cos\alpha_3 + 2F_i(t) \]  \hspace{1cm} (4)

In the formula, \( \alpha_1, \alpha_2, \) and \( \alpha_3 \) respectively represent the angle between the cable ①, ②, ③ line and the wind wave current respectively. When the floating body is in dynamic balance, the resultant force of the cable in the forward wave direction is different from that in the back wave direction by two times of the environmental force load.

\[ F_{m1}(t)\cos\alpha_1 + F_{m2}(t)\cos\alpha_2 \pm (M_g + \mu(x))a(t) = F_{m3}(t)\cos\alpha_3 + 2F_i(t) \]  \hspace{1cm} (5)

In the formula, \( a(t) \) is the dynamic response acceleration of the floating body. When OC4 floating body reaches the dynamic equilibrium in the later stage of time domain analysis, the slow floating motion disappears, and the relationship between mooring taut and environmental force meets formula (4). The characteristics of floating body motion and mooring taut change are similar to that of taut mooring.
Figure 8. Maximum taut of each mooring line in three mooring forms

Figure 8 shows the maximum taut of each cable in the three mooring forms. The three mooring forms satisfy that the taut of ① line and ② line cables is greater than that of ③ line cables, and the taut values of No.1 and ② line cables are relatively close; among them, the maximum mooring force is taut type steel wire mooring, ② line cable is 2708751.75N, and the minimum mooring force is catenary type ③ line 36904.85N. The results show that the maximum taut of mooring line is affected by the mooring side with the increase of mooring flexibility, the maximum mooring force decreases, which is negatively related to the overall degree of freedom of mooring flexibility.

Figure 9. Time domain response law of three mooring forms under different waves
Taking the maximum response amplitude and the maximum taut in different wave directions, the time-domain hydrodynamic response laws of the three mooring forms shown in figure 9 are obtained. According to figure 9 (a), different wave directions have great influence on the mooring force of taut type steel cable. The maximum taut force is 3609677 N when the wave direction is 60° and the minimum taut force is 1735816.7 N when the wave direction is 120° respectively. The taut force of taut type polyester cable and catenary steel cable is less affected by different wave directions, but the maximum value also appears in 60° direction. According to figure 9 (b) and (c), the hydrodynamic swaying response of catenary steel cable mooring is obtained. The variation of stress amplitude is most affected by different wave directions, with a minimum swing value of 13.4 m at 60° and a maximum swing angle of 14.9° at 80° respectively. The overall average swing value is larger than that of taut polyester cable and catenary cable. The results show that the amplitude of the hydrodynamic response of the catenary cable varies obviously under different wave directions. The 60° wave direction is the sensitive area of the hydrodynamic response of the mooring floating body, which is the key factor affecting the safe operation and research analysis of the three-point mooring system.

4. Conclusion
In this paper, the dynamic response law and difference between taut mooring and catenary mooring are studied by taking OC4 as hydrodynamic model.

(1) In the process of time domain analysis, different mooring forms and mooring materials have a great impact on the hydrodynamic response of the floating body. Due to the large flexible elongation of catenary mooring line, the floating body will appear attenuation slow drift motion in the early stage of time domain analysis. When the mooring taut and wind wave current environmental force gradually reach dynamic balance, the slow drift motion gradually disappears and the free degree of freedom response of the floating body in the surge process. The results show that the law of sinusoidal variation is presented; due to the small flexible elongation of the cable, the taut mooring system is a relatively stable low amplitude harmonic motion in the whole process of time domain analysis.

(2) The variation law of mooring taut and dynamic stability of floating body under different waves is simulated. It is found that the taut of taut type wire rope changes obviously, and the hydrodynamic response amplitude of catenary wire rope changes obviously, and reaches the extreme value at about 60° in the wave direction, which is mainly affected by the nonlinear restoring force stiffness of mooring and the free elongation of the cable in different directions.

(3) Combined with the coupled motion equation of floating body and the time domain response analysis results of the two mooring systems, the dynamic response equations of taut mooring and catenary mooring are improved, which provides a theoretical basis for the in-depth analysis of mooring dynamic response.

5. References
[1] Robertson A, Jonkman J, Masciola M, et al. Definition of the semisubmersible floating system for phase II of OC4[R]. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2014.
[2] Zhang Liang, Li Hui, Ma Yong, Zhang Wei, Du Chengren. Study on a combined mooring system and its mooring characteristics[J]. Ship mechanics, 2016, 20 (03): 306-314
[3] Coulling A J, Goupee A J, Robertson A N, et al. Validation of a FAST semi-submersible floating wind turbine numerical model with DeepCwind test data[J]. Journal of Renewable and Sustainable Energy, 2013, 5(2): 023116.
[4] Goupee A J, Koo B J, Kimball R W, et al. Experimental comparison of three floating wind turbine concepts[J]. Journal of Offshore Mechanics and Arctic Engineering, 2014, 136(2): 020906.
[5] Couling A J, Goupee A J, Robertson A N, et al. Importance of second-order difference-frequency wave-diffraction forces in the validation of a fast semi-submersible floating wind turbine model[R]. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2013.
[6] Kim H C, Kim M H. Comparison of simulated platform dynamics in steady/dynamic winds and irregular waves for OC4 semi-submersible 5MW wind-turbine against DeepCwind model-test results[J]. Ocean Syst. Eng, 2016, 6(1): 1-21.

[7] Fan Hao, Zhu Keqiang, sun zhaohao, et al. Comparative study on mooring system of offshore semi submersible floating wind turbine platform [J]. Shipbuilding Engineering, 2017 (7): 84-90

[8] Liang Mingxiao, Wang Xuefeng, Xu Shengwen, Ding Aibing, Shang Yongzhi. Simplification of VLFS single module mooring system based on mooring static similarity [J]. Ship mechanics, 2020,24 (01): 49-62

[9] Li Yan, Tang Yougang, Liu Shuxiao, et al. Fatigue characteristics analysis of single point mooring system of internal turret FPSO [C] the Eighth Plenary Meeting of ship mechanics Academic Committee of China Society of shipbuilding engineering. 2014

[10] API D. Analysis of station keeping systems for floating structures[J]. API RP 2SK, 3rd edition, American Petroleum Institute, Washington DC, USA, 2005.

[11] Fang Lei. Research on fatigue life assessment method of mooring line for Spar platform [D]. Tianjin University, 2008.

[12] Wang Haoran, Wei Yuefeng, pan Fanghao. Fatigue life of single point mooring FPSO mooring line [J]. Ship, 2015 (2): 101-105.

Acknowledgments
This work is financially supported by the Qingdao West Coast new area science and technology project in 2019 (2019-8) "Research on Key Technologies of marine fishery electricity integrated development system" and National Natural Science Foundation of Shandong China Joint Fund (No.cv2017-kf-02).