Numerical Study of Typhoon Resistance of a Floating Wind Turbine

Liwei Zhang*, Boyuan Qiu, Li Ren and Xin Li

1College of Mechanical and Power Engineering, Dalian Ocean University, Dalian, 116023, China
2State key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, 116026, China
*Corresponding author’s e-mail: zhangliwei@dlou.edu.cn

Abstract: Numerical model of a floating wind turbine is established by reference to the 5 MW wind turbine of American national renewable energy laboratory (NREL). CFD method and Morison formula are used to calculate the wind and wave load under typhoon conditions. According to the geometric distribution of mooring system, the static extreme tension of the chains is estimated, and a safety factor of 3 is used to determine the nominal diameter of the chains. The nonlinear finite element iterative algorithm is adopted to calculate the initial shape and length of the chains, and then the dynamic response of the structure and tensions of the chains under coupled wind and wave actions are obtained through AQWA. The analysis results show that the floating wind turbine is stable under the action of typhoon and waves, the maximum surge displacement of the spar is 10.9 m and the maximum pitch angle is 10.4°, and the maximum tension of the mooring system is smaller than the breaking load.

1. Introduction

In recent years, with the increasing demand for clean energy, offshore wind power is becoming an important direction of energy development. The safety of offshore wind turbines is particularly important because of their higher cost and more complex operating environments. It is generally believed that in the sea with a depth more than 60 m, it is more difficult and costly to develop the stationary turbines, while the floating wind turbine is a more appropriate choice. At present, the floating wind turbine in the world is still in the researching stage, the technology is still immature, especially in the anti-typhoon performance it needs a lot of work to do. Karimirad et al. [1] calculated and analysed the dynamic response of NREL 5MW Spar type concept wind turbine under extreme sea conditions and shutdown conditions, and verified the viability of the wind turbine under severe sea conditions. Zhou tao et al. [2] studied the dynamic response of 6MW SPAR floating wind turbine under second-order wave force by using SESAM and FAST software, and believed that the second-order slow drift force had significant influence on the heave motion of floating wind turbine. Ding qinwei et al. [3] realized the secondary development of AQWA through FORTRAN programming, and based on the radiation/diffraction theory, they compared and studied the influence of the slingboard and its installation position on the dynamic response characteristics of the floating wind turbine Spar platform. Ma et al. [4] used FAST software to analyse the motion and chains tension load of single-column floating wind turbine under typical environmental conditions. Li et al. [5] wrote the code to simulate the motion response of semi-submersible floating wind turbine with
MATLAB and verified it through model experiments. ZHAO et al. [6-7] investigated a multi-column tension-leg-type floating wind turbine (WindStar TLP system) subjected to combined aerodynamic and hydrodynamic loads varying both in time and amplitude for its global performance under normal operating conditions and when parked by using a fully coupled aero-hydro-servo-elastic time domain simulation tool FAST, and the key response variables are obtained and compared with those for an NREL 5 MW baseline wind turbine installed on land.

From the perspective of contents and methods, the buoyancy of the foundation, the initial tension of the chains and the typhoon resistance of the mooring system have not been fully studied, and a simple and effective design process has not been formed. Therefore, it is meaningful to develop a simple and universal numerical analysis method to study the typhoon resistance of a floating wind turbine.

2. Parameters and load

2.1. Wind and wave
In recent years, there have been many typhoons landing in the southeast coastal areas of China, causing great damages. The data of typhoon, including wind and waves, are usually given by the near shore weather station, while the parameters of wind and waves in open sea are rarely reported. "Vesant", international no. 1208, was the strongest typhoon that landed in Guangdong province China in 2012, whose maximum gust speed near the coast is 38.2m/s. However, the maximum average wind speed of 10min measured at Lufeng station of offshore oil platform (21.5°N, 116.1°E) was 24m/s, and the maximum gust wind speed was 29m/s, and the corresponding maximum wave height is 9.74m and the wave period is 9.5s[8]. In this study, the data from Lufeng station are used, and the water depth is assumed to be 100m and the wave is simplified into regular wave. According to the general relationship between wave length, period and water depth [9], a period of 10s and a wave length of 156m were taken as the basic wave parameters.

2.2. The structure
The wind turbine has a single column foundation (Spar type). The mooring system consists of a set of vertical chains and three sets of diagonal chains. The three groups of diagonal chains were 120° apart from each other, and the three chains in each group were 15° to each other. Diagonal chains and wind turbine vertical centre line are apart at an angle of 60°, the layout is shown in Figure 1. The fairleads of diagonal chains are located at 15m below the calm water line. The buoy has a diameter of 12m, total height (excluding the transition section) 60m, and the height below the calm water line is 55m, looking at Figure 2 for details. The tower is designed independently with conical profile, having a total height of 87.6m, and the total weight of the tower is 330t.

The superstructure of the wind turbine, including blade, hub and nacelle, refers to the parameters of the 5MW standard wind turbine provided by the U.S. renewable energy laboratory [10], as shown in Table 1.
Figure 1. Structure and mooring system of the floating wind turbine

Figure 2. Size of the buoy foundation

Table 1. Design parameters of the rotor and nacelle

| Component | Weight (kg) | Center of mass | Moment of inertia (kg m²) |
|-----------|-------------|----------------|--------------------------|
| Blade     | 17740       | 20.475 m w.r.t. Root along the preconed axis | 11776047 w.r.t. Root  |
|           |             | 2.40m above the tower top |                           |
| Hub       | 56780       | (Tower top 87.6m above bottom flange) | 115926 About the shaft |
| Nacelle   | 240000      | 1.91m from yaw bearing center wind down, 1.75m above the tower top | 2607890 About the yaw axis |

2.3. Buoyancy and wave load

The depth of the buoy below the static water surface is controlled by ballast water and pretension of the chains, and the ballast water depth is 25m. During wave propagation, the net buoyancy of the buoy changes periodically, as shown in Figure 3. The maximum net buoyancy is 23430kN, the minimum
net buoyancy is 12130kN, and the net buoyancy of calm water is 18580kN. Here T =0 is the time when the wave crest passes through the buoy.

Figure 3. Net buoyancy of spar

In order to simplify the calculation of the buoy wave force, the buoy is divided into 6 segments with a length of 10m, which are numbered 1 to 6. Segment 1 is the bottom of the buoy, while segment 6 is at the calm water line. Assuming that the structure is still, the calculations of wave force refer to the method proposed in China code of hydrology for harbour and waterway [11]. For small scale structures with D/L \leq 0.2, when H/d \leq 0.2 and d/L \geq 0.2, the horizontal wave force acting on the column of unit length at height z above the seabed can be calculated by Morison formula:

\[ P_W = P_D + P_I = \frac{1}{2} C_D \rho A u |u| + \frac{1}{2} C_M \rho A g \frac{\partial u}{\partial t} \]

\[ u = \frac{\pi H \cos \theta z}{T} \frac{\sin \theta z}{\sin \theta T} \cos \theta t \]

\[ k = \frac{2\pi}{L} \]

\[ \omega = \frac{2\pi}{T} \]

Where: \( P_W \) - velocity component of wave force; \( P_I \) - inertial component of wave force; \( C_D \) - velocity force coefficient, 1.2 for the circular section; \( C_M \) - inertia force coefficient, take 2.0 for circular section; \( D \) - cylinder diameter; \( A \) - the cross section area of the cylinder; \( u \) - Velocity of fluid particle at position of u-cylinder; \( L \) - wavelength; \( H \) - wave height; \( T \) - wave period; \( k \) - wave number; \( d \) - water depth; \( \gamma \) - water weight; \( G \) - gravitation acceleration; \( \omega \) - the circular frequency of the waves; \( t \) - time, when the wave crest passes through the centre line of the cylinder, \( t=0 \).

The horizontal wave forces on different sections of the buoy are shown in figure 4. The horizontal wave force of the whole buoy is obtained by adding up the wave forces of all the sections, with a maximum value of 9893kN.

2.4. Wind load

Wind loads are calculated using the method of computational fluid dynamics (CFD). The maximum gust wind speed of 29m/s was taken as the simulated wind speed. Since the wind direction and wind speed sensors are installed on the top of the drilling tower with an altitude of 82m, and considering the wind shear effect, the wind speed at different altitudes is firstly calculated [12]:

\[ \bar{u}_z = \bar{u}_0 \left( \frac{z}{z_0} \right)^\alpha \]

Where: \( z_0 \) - is the height of the reference point; \( \bar{u}_0 \) - is wind speed of reference point; \( \alpha \) - stand for the wind shear index, which is 0.14.

Modeling and simulation of the flow field are performed in Fluent, as shown in Figure 5 and Figure 6. Because the wind speed is higher than the cut-out speed of the wind turbine, the yaw and pitch control system automatically make the rotor windward locked and the blades feathering. The modelling of flow field adopts mixed grids, and the field adjacent to the blades is refined with a minimum grid size of 0.3m.
Figure 5. CFD model of wind turbine

Figure 6. Simulation of wind load

Figure 7 shows the iterative results of horizontal thrust forces of the rotor and tower. The horizontal thrust of the rotor and tower is 223kN and 450kN respectively. This tells that the horizontal thrust of the wind is smaller than 1/10 of the maximum wave load.

3. The mooring system

According to the maximum force on the spar and the geometric distribution of mooring lines, the maximum axial tension of the diagonal chain caused by wave is estimated to be 3810.6kN. In the preliminary design, the safety factor is set to 3. R4 classed marine mooring chain with diameter of 114mm is selected, which has a density of 282kg/m and a breaking load of 12420kN. The system also has 3 vertical chains, with nominal diameter of 132mm and breaking load of 15965kN.

In the calm water condition, the net buoyancy of the spar foundation is 18580kN. For preliminary design, the vertical chains undertake the buoyancy of 13000kN and 5580kN by the diagonal chains.
According to this objective, the nonlinear finite element iterative algorithm (Newmark method) was used to calculate the initial shape and tension of the diagonal chains.

The basic principle of iteration is to establish a straight line firstly between two endpoints of the diagonal chain, and to mesh the line into a finite element model according to the equivalent cross section and physical parameters. When the chain deforms under the action of gravity, the axial tension and vertical component of the tension are read and inspected, as shown in Figure 8. If the error between the vertical component of the tension and the target value is larger than 0.5%, regenerate the model from the shape of the chain after deformation and repeat the calculation and inspection, until the error is equal to or smaller than 0.5%. When the iteration is finished, the length and the shape of the chain are determined. The result is shown in Figure 9.

4. Analysis and discussion

The dynamic performance of wind turbine and mooring system against typhoon is simulated and analysed by means of hydrodynamic software ANSYS/AQWA. The 3D model imported in AQWA is shown in Figure 10(a), in which the definition of six degrees of freedom of the wind turbine under the action of wind and wave is given, and the wind and wave direction is perpendicular to the rotor plane. The mass of the structures is simplified into concentrated mass elements, and the thin-walled structures are discretized by surface elements, as shown in figure 10(b). The length of chains is set to 172m according to the previous calculation. Airy Wave model is adopted to simulate regular waves for wave loads and constant wind speed model for wind loads.
Figure 11(a) and Figure 11(b) are respectively the time history curves of surge and pitch of the spar. From the curves it can be seen that the time domain responses of wind turbine under the action of extreme wave and wind have no divergent trend and the system is stable. The maximum surge displacement of the spar centroid is 10.9m, and the maximum pitch angle is 10.4°.

Figure 12 show respectively the tension time history of chain 1, 2 and 3. It reveals that the tensions of the three chains vary with the same trend, while, the tension of chain 2 is larger, with a maximum
value of 11231.7kN. The fact tells that all the tensions of the chains are smaller than the breaking load and meets the safety requirements.

5. Conclusions
In this work, the mooring system of a 5MW floating wind turbine is preliminarily designed based on the typhoon and wave load, and the nominal diameter of the chains is determined according to the safety factor of 3. The nonlinear finite element iterative algorithm is used to calculate the initial shape and length of the chains. The dynamic response analyses of the structure and mooring system are carried out by AQWA. The analysis results show that under extreme typhoon conditions, the system is stable and all the tensions of the chains are smaller than the breaking load.

Acknowledgements
This work was Financially supported by the national natural fund of China (51879040), open fund of State key laboratory of coastal and offshore engineering of Dalian university of technology (LP1925, LP 1914) and Fund of education department of Liaoning province China (JL201911 , JJW201915402).

References
[1] Karimirad, M., Moan, T. (2011) Extreme dynamic structural response analysis of catenary moored spar wind turbine in harsh environmental conditions. J. Offshore Mech. Arct. Eng., 133(4): 41103. https://doi.org/10.1115/1.4003393.
[2] ZHOU, T., HE, Y. P., MENG, L. (2018) Dynamic response analysis of a 6 MW spar-type floating offshore wind turbine under second-order wave forces. Journal of Harbin Institute of Technology, 50(4):145-152.
[3] DING, Q. W., LI C., YUAN, W.B. (2019) Effects of Heave Plate on Dynamic Response of Floating Wind Turbine Spar Platform Under the Coupling Effects of Wind and Wave. Proceedings of the CSEE, 39(4):1113-1126.
[4] MA, Y., HU, Z. Q., XIAO, L. F. (2015) Wind-wave induced dynamic response analysis for motions and mooring loads for a Spar-type offshore floating wind turbine. Journal of Hydrodynamics, 26(6):865-874.
[5] LI, L., HU, Z. Q., WANC J., et al. (2015) The development and validation of an aero-hydro simulation code for offshore floating wind turbine. Journal of Ocean and Wind Engineering, 2(1):1-11.
[6] Zhao, Y.S., Yang, J.M., He, Y.P. and Gu, M.T. (2016) Coupled dynamic response analysis of a multi-column tension-leg-type floating wind turbine. China Ocean Engineering, 30(4): 505-520.
[7] Zhao, Y.S., Yang, J.M., He, Y.P. and Gu, M.T. (2016) Dynamic response analysis of a multi-column tension-leg-type floating wind turbine under combined wind and wave loading, Journal of Shanghai Jiaotong University (Science), 21(1):103-111.
[8] Zhuang H. B., Gao R. Q., Fan W. L. (2013) Characteristics of the waves in the effect of tropical cyclone. Meteorological, Hydrological and marine instruments, 2:30-34.
[9] YU, Y.X. (2000) Random wave and its application to engineering. Dalian University of Technology Press, Dalian.
[10] Jonkman, J., Butterfield, S., Musial, W. (2009) Definition of a 5 MW reference wind turbine for offshore system development, National Renewable Energy Laboratory.
[11] Ministry of Transport of China. (2015) JTJ 145-2015 Code of hydrology for harbour and waterway. China Communications Press, Beijing.
[12] Deng, L., Xiao, Z. Y., Huang, M.X. (2015) Numerical Simulation of Dynamic Response for Offshore Wind Turbines including Fluid-Structure Interaction. Journal of Hunan University (Natural Science Edition), 42(7):1-8.