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Influence of Mooring Tension on Dynamic Performance of Semi-submersible Wind Turbine under Typhoon Condition

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Abstract: A numerical model of a 5 MW semi-submersible wind turbine is established based on the reference wind turbine of American national renewable energy laboratory (NREL). The nominal diameter of the mooring chains was determined after the static wind load and wave load of the turbine under the action of typhoon being calculated by CFD method and Morison method. Finally, the dynamic responses of the turbine and the internal forces of the chains are obtained by the dynamic finite element analysis for three cases. The results show that when pretension chains are used, the turbine motion frequency is consistent with wave frequency, the surge is small, the pitch is reciprocally symmetrical, and the peak internal force of the chains is quite high. When mooring chains without pretension are adopted, the motion of the turbine consists of low-frequency drift and forced motion in sync with the wave frequency, the pitch is asymmetrical, and the internal tension force of the chains is relatively low.

1. Introduction

In recent years, with the increasing shortage of energy, the increasing pressure of environmental protection and the increasing demand for clean energy, offshore wind power is becoming the focus of people's attention and a new direction. The safety of offshore wind turbines is particularly important because of the extremely complex operating environment of offshore wind, wave and ocean currents. At present, the stationary offshore wind turbine has been widely used and a lot of research achievements have been made [1-4], but floating wind turbines are still in the conceptual design stage, and the technology is still relatively immature, requiring extensive research. Karimirad et al. [5] determined and analyzed the extreme response of a 5MW Catenary Moored Spar wind turbine in Harsh Environmental Conditions by coupled aero hydro-elastic time domain simulation, considering coupled wave and wind induced motion and structural response, and checked the strength of the wind turbine for ultimate limit state. Zhou [6] simulated the coupled motion response of a new 6MW offshore spar floating wind turbine in time domain by using the air-liquid-solid-elastic numerical software FAST and discussed the effects of second-order average wave force and second-order slow-drift wave force on the motion response of the platform and on the tension of anchor chain and the acceleration of the engine room. Zhang [7] designed and studied the mooring system of 5MW Spar wind turbine for typhoon conditions, and analyzed the motion response of the turbine platform and dynamic force of the chains. Yue et al. [8] realized the secondary development of AQWA through



FORTTRAN, established a model composed of OC3-Hywind Spar Buoy platform and NREL 5MW wind turbine, and explored the influence of the heave plate and its installation position on the nonlinear dynamic response of the floating wind turbine. ZHAO et al. [9] investigated the coupled dynamic response of a tension-leg-type floating wind turbine (Wind Star TLP system) subjected to combined wind and wave loads varying both in time and amplitude under normal operation and parked conditions to identify the dominant excitation loads and the safety factor of the tension mooring system by using FAST. LIU [10] established three typical semisubmersible floating wind turbine foundations (OC4, Windfloat and Ideol) and their hydrodynamic models, and compared the time-domain motion responses of the three floating wind turbine foundations under different wind, wave and current combined effects and their adaptability under different water depths in the South China Sea.

In terms of the current research status, there are fewer researches on semi-submersible turbine, and especially the researches on ballast, mooring tension design and typhoon resistance of floating turbines are still insufficient. Therefore, it is necessary to do further research on the semi-submersible turbine and its mooring system, which has certain reference significance for the design of the survivability of this kind of turbine under typhoon.

2. Structure system and load

2.1. Typhoon and wave

Typhoons have hit southeastern China every summer for the past decade, causing huge damage. Typhoon and wave information is usually provided by inshore weather stations, while there are few datas for wind and wave at sea. "Vesant", international no. 1208, is the strongest typhoon that landed in Guangdong province China in 2012. The maximum gust wind speed measured at Lufeng station on offshore oil platform (21.5°N, 116.1°E) was 29m/s, the corresponding maximum wave height is 9.74m and the wave period is 9.5s[11]. In this paper, the designed water depth is 100m. By reference to the general relationship between water depth, wave length and period of deep water wave[12], the wave length is set to 156m.

2.2. The structure

Wind turbine foundation adopts three buoy type structure, and the distance between the three buoys is 70m. The diameter of the buoy is 12m, and the height is 20m, of which the height below the static water surface is 15m. The mooring system is composed of 3 groups of mooring chains with circumferential intervals of 120°, and three anchor chains in each group are 15° apart. The overall layout is shown in Figure 1. The tower is designed independently and adopts conical structure, having a total height of 87.6m. The diameter increased from 3.6m to 6m from tower top to bottom, the wall thickness increased from 20mm to 40mm, and the tower has a weight of 330t.

The parameters of the superstructure, including the blade, hub and engine room, is shown in table 1[13].

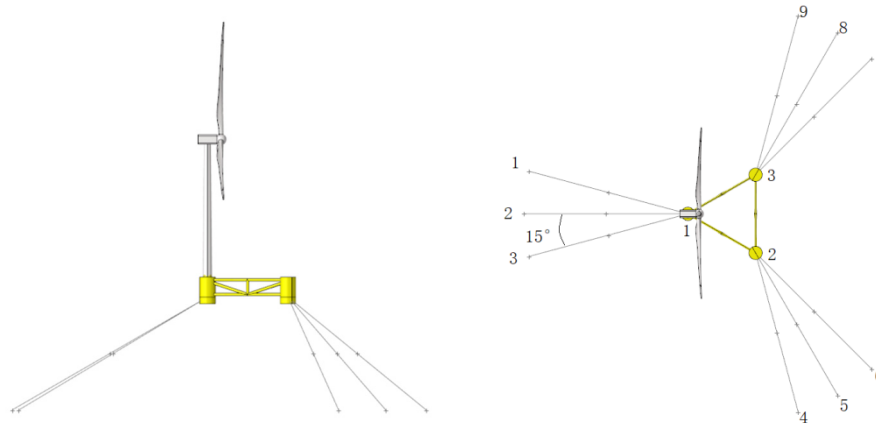


Fig.1. Structure of wind turbine

Tab.1 Design parameters of the rotor and nacelle

	Weight (kg)	Center of mass	Moment of inertia (kg·m ²)
Blade	17740	20.475 m w.r.t. Root along the preconed axis	11776047 w.r.t. Root
Hub	56780	2.40m above the tower top (Tower top 87.6m above bottom flange) 5.000m from the yaw-bearing center	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. wave load

The length of the buoy below the still water is 15m, controlled by ballast water and mooring tension. Assuming that the platform is still, the horizontal wave force can be calculated with the Morison method proposed in China hydrology code for harbor and waterway[14]:

$$P_W = P_D + P_I = \frac{1}{2} \frac{\gamma}{g} C_D D u |u| + \frac{\gamma}{g} C_M A \frac{\partial u}{\partial t} \quad (1)$$

$$u = \frac{\pi H}{T} \frac{\cosh kz}{\sinh kd} \cos \omega t \quad (2)$$

$$k = \frac{2\pi}{L} \quad (3)$$

$$\omega = \frac{2\pi}{T} \quad (4)$$

Where: P_D -velocity force; P_I -inertial force; C_D -velocity force coefficient, taking 1.2 here; C_M -inertia force coefficient, 2.0; d -water depth; D - diameter of the column; A - the cross section area; u -Velocity of fluid particle; T -wave period; L -wave length; H - the wave height; k -wave number; γ - weight of water; ω -circular frequency; t -time, $t=0$ when the wave crest is over the center line of buoy1.

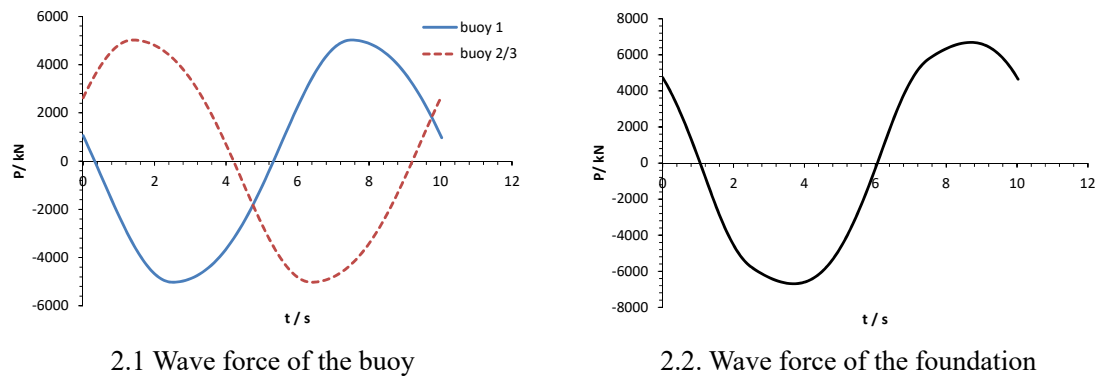


Fig.2 The wave force

The horizontal wave force of the buoy and the platform were calculated through Equations (1) ~ (4), as shown in figure 2. It can be seen that in the process of wave propagation, the wave force of the buoy changes periodically with wave propagation. The maximum wave force of the buoy is 5022kN. Meanwhile, due to the large size of the platform, the peak time of wave force of No. 1 buoy is not consistent with that of No. 2 buoy and No. 3 buoy. The total wave force of the platform is shown in figure. 2.2, and the maximum wave force is 6690kN.

2.4. Wind load

CFD method is used to calculate the wind load. The calculation results of the wind load on the rotor and tower are shown in figure 3, for specific calculation process, see reference [7].

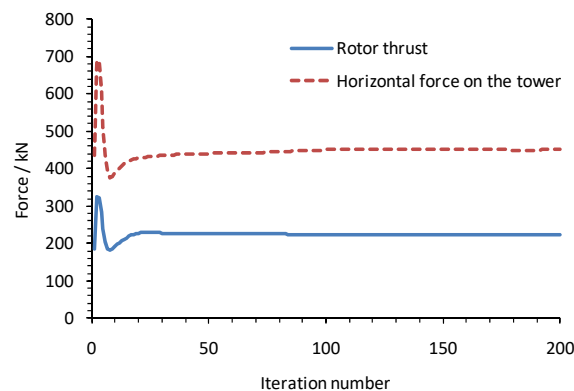


Fig. 3. Results of wind load

3. Mooring system

For semi-submersible wind turbine, the mooring system is very important, which determines the stability and safety of the wind turbine. According to the maximum resultant force on the foundation and the mooring lines distribution, the maximum tension of the chains is calculated. For conception design, a static safety factor of 3 is adopted. R4 class marine chain with diameter of 114mm is selected, which has a density of 282kg/m and a breaking load of 12420kN.

Under the action of gravity, the tension of the chains with different lengths varies greatly. firstly Newmark iterative algorithm was used to determine the relationship of initial length and tension.

The method of iteration is to build a straight line between the two ends of the chain, and then the line is separated into finite elements, and deformation of chain occurs under gravity. Meanwhile, the axial tension force and angle of the low end element of the chain are detected, as shown in Figure

4. If the angle is less than 0.5%, the low end element is removed, the model is reconstructed according to the deformed line of the chain, and the total length of the chain is calculated. The iteration will continue until the total length of anchor chain is close to the given value, then the tension of the chain of a given length is got.

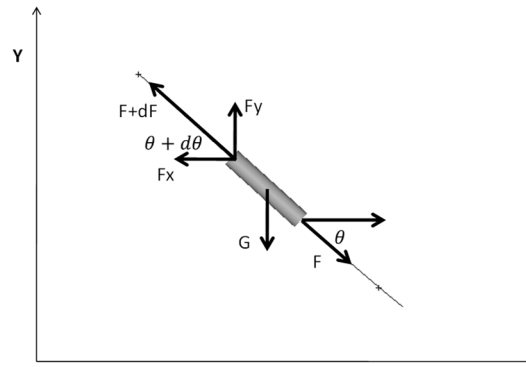


Fig.4. Tension and angle of the chain

4. Dynamic analysis and discussion

ANSYS/AQWA is used to determine the coupled dynamic motions of wind turbine and mooring tensions under typhoon and wave. The 3D model shown in figure 5, in which the six degrees of freedom of the platform is defined, and the wind and wave direction is perpendicular to the rotor plane.

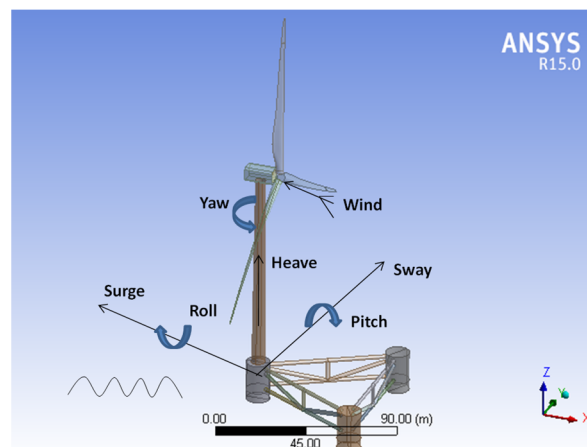


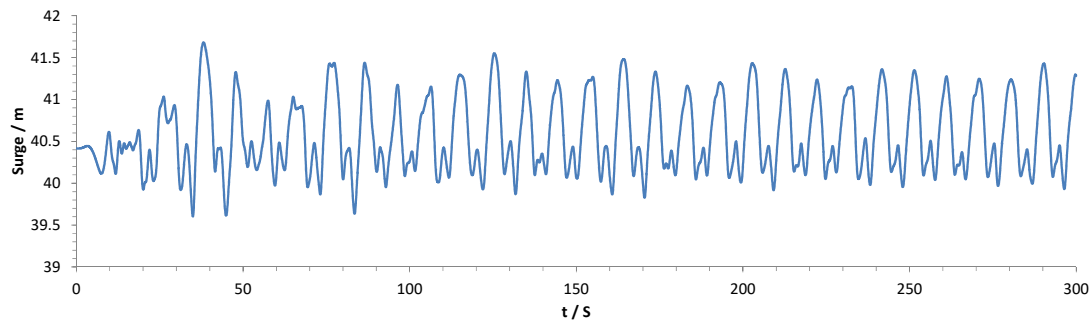
Fig.5. Dynamic model of the wind turbine

To study the influence of chain length and tension on wind turbine dynamic performances under typhoon, three cases are considered. The corresponding chain length, upper tension and buoy weight of the three cases are shown in table 2. It should be pointed out that the upper end and lower anchor point of the chain are same in the three cases.

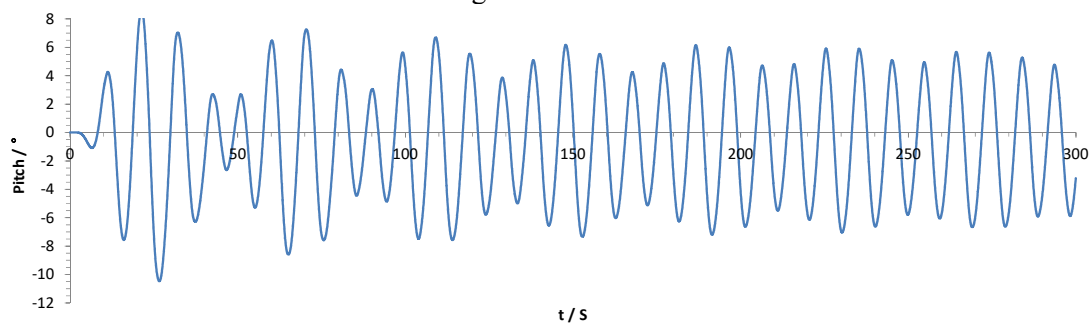
Table2. Three case of the mooring system

	Case1	Case2	Case3
Buoy weight(t)	1253	1580	1640
Chain length(m)	170	180	200
Chain tension force(kN)	3120	479.9	283.4

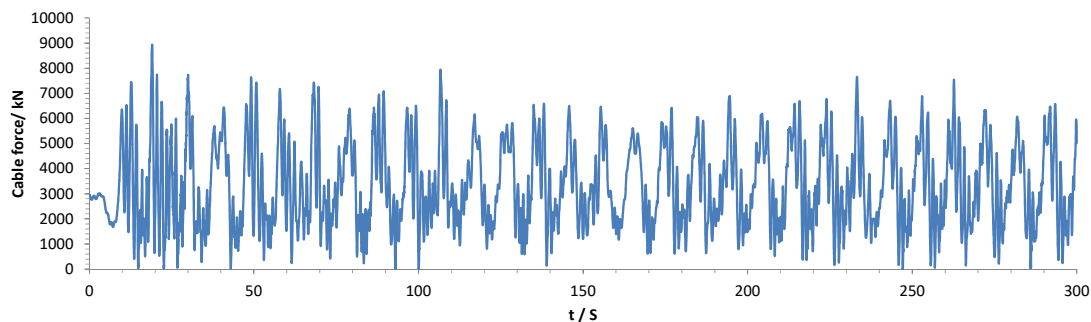
Figure 6 shows the time-history curves of surge, pitch, and tension force of No. 2 anchor chain when the chain length is 170m (tension forces of No. 1 and No. 3 chains are similar but amplitude smaller than No. 2). It can be seen that when using pre-tension chains, the wind turbine has a small amplitude of surge, with the maximum value of 1.3m. The maximum pitch angle is about 11° , and the pitch is reciprocating symmetry around the equilibrium position. The maximum tensile force of chains is 8939.8kN, which is a little less than the breaking force of the chain; the safe factor of the chains is 1.39. In addition, the dynamic response period of the platform is consistent with the wave period.



6.1 Surge of the foundation



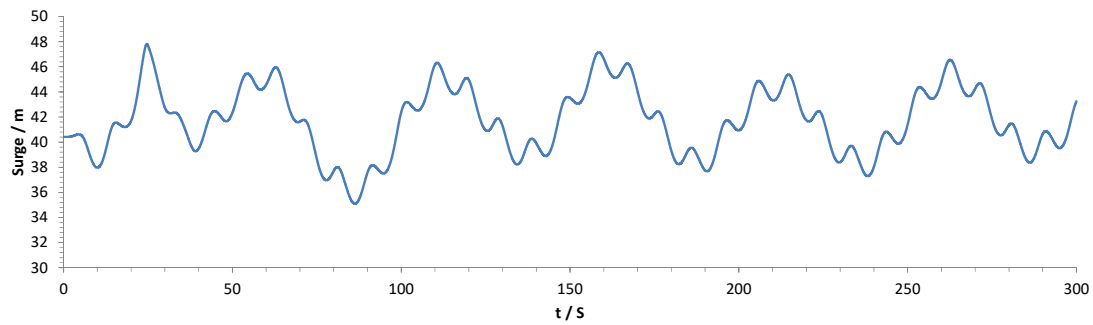
6.2 Pitch of the foundation



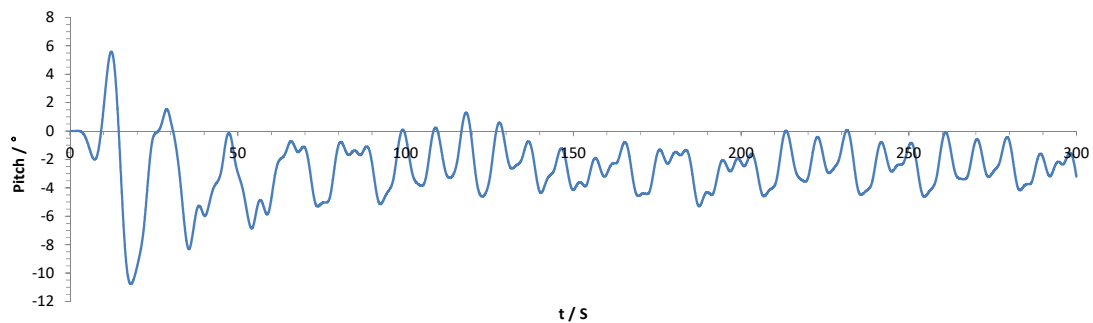
6.3 Tension force of chain 2

Fig.6. Dynamic results of case 1

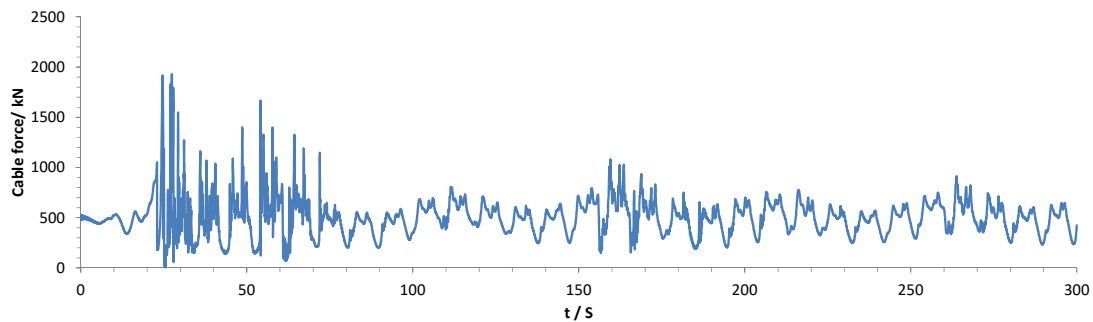
Figure 7 shows the simulation results of case 2. It can be seen that the maximum amplitude of the surge is about 7.4m. It can also be seen from the surge curve that the oscillation is superimposed by low frequency drift and forced motion in sync with the wave frequency. The pitch amplitude of the wind turbine is similar with that of case 1, but it is asymmetrical. In this case, the maximum tension is about 1910kN, and the safe factor of the chains is 6.5.



7.1 Surge of the foundation



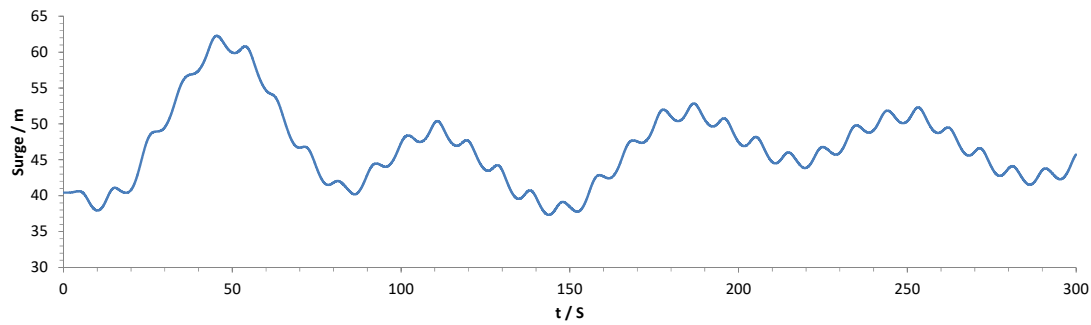
7.2 pitch of the foundation



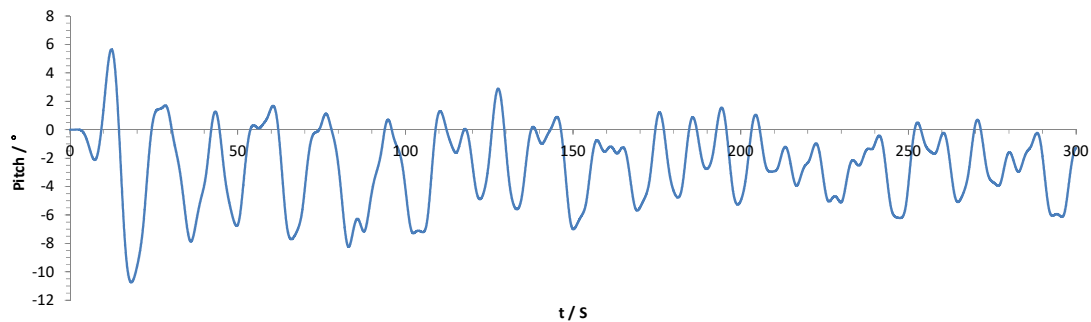
7.3 Tension force of chain 2

Fig.7 Dynamic results of case 2

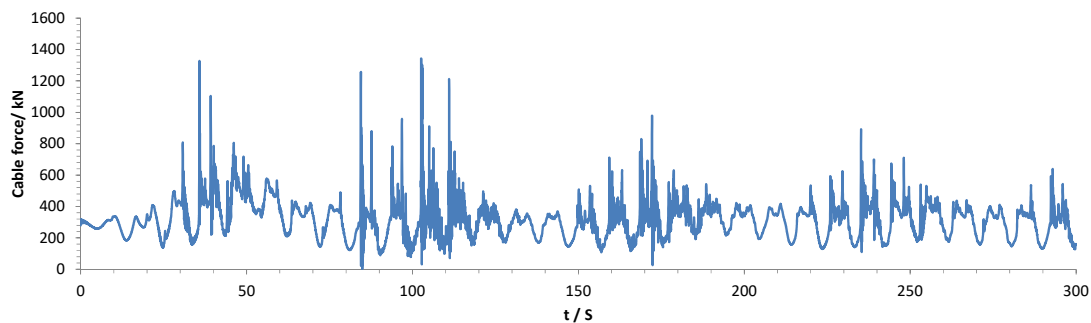
In case 3, the motion pattern of the wind turbine is similar to case 2, but the amplitude of the surge further increases, the maximum value is about 21.9m, and the amplitude along X direction is greater than that in -x direction, as shown in Figure 8. It can also be seen that the motion is mainly low-frequency drift, with a period of about 80 seconds. The tension amplitude of the chain further decreases to 1360kN.



8.1 Surge of the foundation



8.2 pitch of the foundation



8.3 Tension force of chain 3

Fig.8 Dynamic results of case 3

The comparison of responses in three cases is shown in Table 3.

Tab.3. Maximum response in three cases

	Case1	Case2	Case3
Maximum Surge(m)	1.3	7.4	21.9
Maximum Pitch(°)	-10.5	-10.8	-10.7
Maximum tension force(kN)	8939.8	1929.8	1343.1
Safe factor of the chains	1.39	6.5	9.25

5. Conclusions

In this work, the numerical model of a semi-submersible wind turbine is established based on the 5 MW reference wind turbine of American national renewable energy laboratory (NREL). The wind load and wave load of the turbine under the action of typhoon wind and wave were calculated. The mooring system was designed based on the static forces and the dynamic response of the structure under typhoon with different chain length was simulated, the conclusions are as follows:

- (1) When pre-tension chains are used, the amplitude of surge is low, the pitch is symmetrically distributed, the period of the motion is the same as the wave period, and the tension force of the chains is high.
- (2) While mooring chains without pre-tension are used, the oscillation is superimposed by low frequency drift and forced motion in sync with the wave frequency. The pitch amplitude of the wind turbine is almost the same with that using tension chains, but it is asymmetrical. Meanwhile, the chain tension is relative low.
- (3) In brief, with the increase of chains length, the motion range of wind turbine platform becomes larger, while the safety factor of mooring chains increases. The maximum tensions of mooring chains in three cases are less than the breaking force, indicating that it is feasible to design mooring system with a static safety factor of 3.

Acknowledgements

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