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NUMERICAL ANALYSIS OF THE DYNAMIC RESPONSE OF AN INTEGRATED STRUCTURE OF TNE FLOATING WIND TURBINE AND THE FISH CAGE TO REGULAR WAVE

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ABSTRACT

In recent years, offshore wind power and aquaculture industry have developed rapidly and expanded. Considering the sea-use conflict between offshore wind power and aquaculture as well as the development needs, a new designed structure that integrated the floating wind turbine and the fish cage is proposed in this study. This new structure can effectively use the ocean space and achieve a win-win situation between the modern marine aquaculture industry and the renewable energy industry, which is of great significance to both social, economic development and environmental protection. The characteristic of the windenergie-aquaculture integrated structure in this study is that the tower of the wind turbine is connected to the top center of the frame structure of a hexagonal semi-submersible fish cage, and the side columns are as ballast compartments for adjusting the draft and provide sufficient buoyancy. The mooring system is tensioned which is suitable for the deep sea which can mitigate the first order heave, surge and pitch motions. A finite element numerical model is established based on the Morison equation and the mesh grouping method. The dynamic response of the overall structure under wave action is studied. This study has significant reference for ensuring the safe operation of the whole windenergie-aquaculture integrated structure and the efficient utilization of marine space resources.

1 INTRODUCTION

In the past few decades, coastal development space has been continuously compressed, and the supply capacity of marine energy and fishery resources has been unable to meet the growing market demand. Many countries hope to develop large-scale marine aquaculture to make up for the low yield and quality of traditional aquaculture, so as to ensure the supply and safety of marine products. Some fish-farming companies have suggested combining semi-submersible platforms with nets for offshore fish farming. As shown in Figure 1 (a), the "Deep Blue 1" fishery has a diameter of 60 meters and a height of 35 meters. It has a capacity of 50,000 cubic meters and has a central buoy for generating electricity for the cage through vertical oscillating movements.

(a) Deep Blue 1 (b) HyWind (spar) (c) WindSea (semisub) (d) Blue H (tension leg)

Figure 1: Typical offshore fish farm and floating wind turbines

Power transmission over long distances is expensive, and to make faraway aquaculture economically viable, large marine ranches often need free access to a constant source of power, such as solar, wind and wave energy, from the site. At present, the wind turbines in the deep sea area are basically floating foundations, respectively Spar, Semi and TLP, as shown in Figure 1 (b), (c) and (d). Considering the economic factors, the semi-submersible foundation is the best choice when the water depth is more than 50 meters. It is suitable for deep water, can be wet towed transportation, low cost of mooring system. Currently, in addition to many technical challenges, cost reduction is one of the primary key issues for offshore wind turbines (Islam, 2016). Buck and Langan (2017) showed that combining wind farms with aquaculture could reduce the operation and maintenance costs of wind farms by 10%, which would be more conducive to the sustainable development of offshore wind farms.

As an important part of marine economy, the combination of offshore wind power and fishery farming industry is of great significance to social and economic development and environmental protection. A great deal of research has been done on the feasibility and hydrodynamic stability of the windenergie-aquaculture integrated structure. Roddier et al. (2010) proposed Windfloat, a semi-submersible floating wind turbine model, and carried out a feasibility study on the technical performance of Windfloat, including hydrodynamics and structural strength. Holm and Buck (2017) think that while trying to find new marine uses, it is necessary to explore the possibility of locating equipment (such as wind turbines, fish and shellfish farms) in the same location. The concept of juxtaposition of organic seafood and renewable energy production facilities is consistent with the goal of rational planning of marine space and ecosystem-based management. Jansen et al. (2016) took the conditions of the waters of the North Sea in the Netherlands as an example to discuss the feasibility of promoting the development of marine aquaculture and the multi-purpose utilization with other marine activities, and confirmed the possibility of profit from combining mussel production in or around wind farms in the North Sea in the Netherlands. Chu and Wang. (2019) combined the SPAR platform with a partially porous wall fish cage and put forward a design concept of a marine fishery farm. The design features a Spar platform equipped with wind turbines and control units that can provide power for remotely controlled fish farming operations, overcoming the challenges of high-energy environments, inadequate power supply and stable mooring systems for offshore fish farms.

This paper introduces an innovative design scheme of the combination of semi-submersible cage and wind turbine, which makes full use of the space of semi-submersible platform and wind turbine to form a new type of floating wind turbine structure.

2 NUMERICAL METHODS

In this paper, the offshore wind turbine and the semi-submersible aquaculture cage are taken as the research objects. The finite element analysis software ANSYS is used to establish the finite element model for the structural frame and the combined structure with net. Combined with the fifth-order Stokes wave theory and Morrison equation, the hydrodynamic characteristics of the structure under wave action are analyzed.

2.1 Introduction of the windenergie-aquaculture integrated structure

The semi-submersible wind fishing structure consists of two parts: (i) hexagonal semi-submersible cage, which provides buoyancy by increasing or decreasing water in the column, while the central column supports the upper wind turbine. (ii) a 5 MW wind turbine is installed on the top of the central column to provide power for aquaculture cage.

2.1.1 Semi-submersible cage

The semi-submersible cage is hexagonal, with a steel structure frame, with a side length of 40 meters, a maximum distance of 80 meters, a height of 46 meters and a draft of 40 meters, with a total water volume of about 170,000 cubic meters. The inner space of the cage can be subdivided into three sectors to provide different fish for survival. Due to the existence of the top wind turbine, greatly improve the overall structure of the center of gravity position, set in the bottom of the cage 5 meters of lengthened side column and the bottom of the strengthening support to effectively reduce the center of gravity of the combined structure of the wind and fish, and make the cage can be used for shallow sea fixed alone, further reflect its versatility.

Copper alloy net with strong resistance to wind and waves and outstanding antibacterial ability is selected. The actual mesh length is 40 mm and the diameter is 2 mm. Copper alloy net will not easily deform under the blow of big wind and waves, reduce the impact of wind and waves on the fish body, reduce the damage to the fish, in addition, it can reduce the growth of contaminated organisms in the range of the cage and net cleaning costs and increase the oxygen content of aquaculture space, conducive to the health and growth of fish.

The semi-submersible platform usually adopts catenary mooring system and tensioning mooring system. The tensioning mooring system has a better positioning performance than catenary mooring system. In this study, the height of the middle and upper structure is large, and the motion amplitude of the semi-submersible platform needs to be controlled as much as possible, so the tensioned mooring mode is adopted, and the cross-section area of the cable is 262 cm^2.

2.1.2 Wind turbines

The 5 MW wind turbine at the top of the central column of the cage has a tower height of

87.6 meters, three blade lengths of 61.5 meters, a cabin length of 12 meters, a diameter of 4.8 meters, and a total mass of 807,460 kg. The wind turbine can provide an average of 120,000 kilowatt-hours of electricity per day for the cage farming system, greatly reducing the cost and difficulty of long-distance power transmission on land, and effectively promoting the development of fishery farming to the far sea. The semi-submersible cage device can be used as the foundation of the offshore floating wind turbine. The three upper beams of the cage part are connected with the central column to support and reinforce the wind turbine, and form a walkway to facilitate the maintenance and maintenance of the wind turbine. The base ring is pre-installed on top of the cage central column, and the wind turbine tower and the base ring are bolted together to realize the rapid installation of the two structures. The wind turbine tower and turbine can be combined with the semi-submersible central column of the cage at the wharf and towed to its operation site by tugboat.

2.1.3 The windenergie-aquaculture integrated structure materials and dimensions

The cage frame and wind turbine tower in this paper are made of steel, with a density of 7850 kg/m^3, a Poisson's ratio of 0.3, and an elastic modulus of 2.06×10^5 MPa. The net is made of copper alloy material with a density of 2350 kg/m^3, Poisson's ratio of 0.34, elastic modulus of 2.0×10^{11} MPa, wire diameter of 2 mm and mesh size of 40 mm. Table 1 and Table 2 summarize the detailed parameters of the windenergie-aquaculture integrated structure.

Table 1: Structure parameters of the semi-submersible cage in this study

Component	Length (m)	Diameter (m)	Thickness(m)
Upper arc pipe	40	2	0.02
Middle arc pipe	40	2	0.017
Lower arc pipe	40	2	0.02
Thick column	46	6	0.03
Thin column	46	4	0.03
Inclined column	56	2	0.017
Central column	50	8	0.05
Brace	40	2	0.02
Upper brace	40.3	2	0.02
Lower inclined brace	20.4	1	0.01
Mooring rope	300	0.042	0.021

Table 2: Structure parameters of the wind turbine in this study

Component	Blade	Tower	Nacelle	Hub
Length (m)	61.5	87.6	12	\
Mass (kg)	3*17740	347460	240000	56780

2.2 Finite element model

In this study, the wind turbine, cage frame and net are simulated by PIPE59. PIPE59 element is a uniaxial element and cable element which can withstand tension, compression and bending, and could simulate loads from ocean waves and currents. It is suitable for stiffness hardening and nonlinear large strain problems. The pipe element can effectively simulate the hydrodynamic characteristics of the cage and reduce the problem of low computational efficiency caused by the large number of grids brought by the solid element. At the same time, the mesh-grouping method is used to reduce the amount of grids for computational efficiency (Bi et al., 2014).

Link180 element is used to simulate the cable. This three-dimensional rod element is a tension and compression unit in the direction of the rod axis, and each node has three translational degrees of freedom along the *x*, *y* and *z* directions of the coordinate system. In order to clearly distinguish the positions of various types of bars, different colors are used here to mark, as shown in Figure 2.

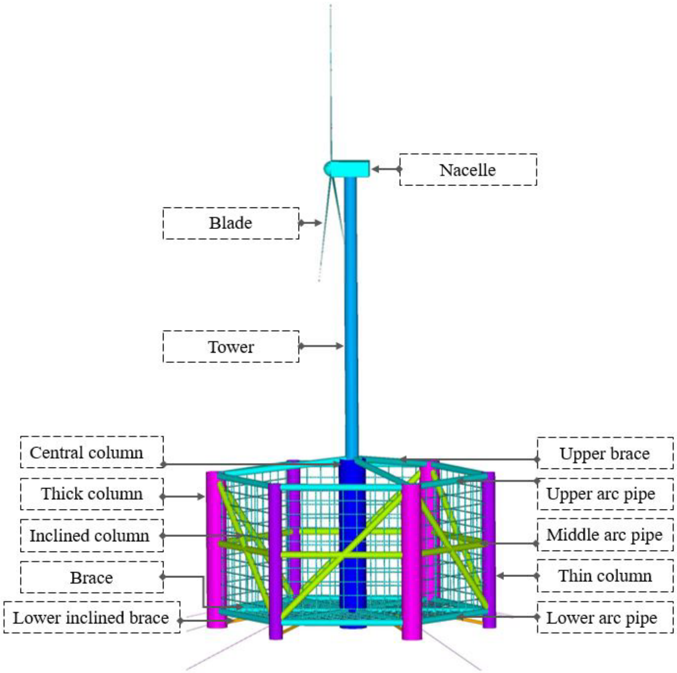


Figure 2: Finite element model of the semi-submersible windenergie-aquaculture integrated structure

2.3 Computational grid

The numerical model adopts Cartesian coordinate system (*x*, *y*, *z*). The origin of coordinates is set at the water surface, *x* direction is the direction of incoming waves, *y* direction is located at the water surface and perpendicular to *x* direction, and *z* direction is perpendicular to the water surface and upward. The reasonable density of grids was determined through the influence of grid encryption on the calculation results, so that the calculation results could meet the accuracy requirements. In this study, each grid length was 0.5 meters, and there were 16,058 grids in total. And the measuring points are all shown in Figure 3.

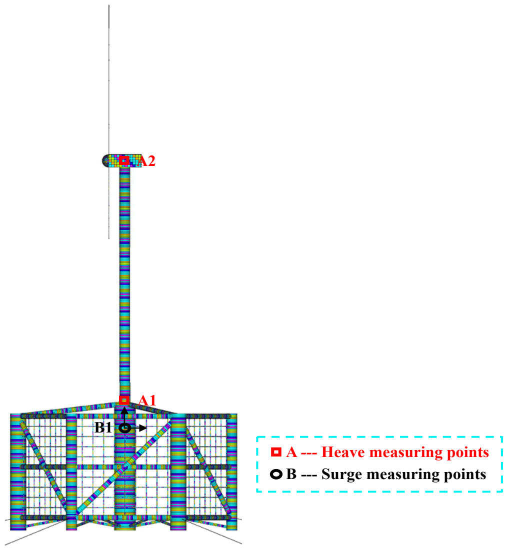


Figure 3: Schematic diagram of the computational grid and measuring points of the semi-submersible windenergie-aquaculture integrated structure

2.4 Experimental conditions

In actual environment, the superstructure of the windenergie-aquaculture structure is mainly subjected to wind load, while the lower semi-submersible cage foundation is mainly subjected to wave and current load. Since the diameters of the side columns are not completely consistent, the structure is symmetric only in the x direction. In this paper, the influence of wave incident from different directions on the motion response of the structure is also considered. The environmental load of the wind fishing structure is mainly the regular wave force of 0°, 45° and 90° incident directions, and the wave elements of regular waves are shown in Table 3.

Table 3: Wave conditions

Wave Case No.	Wave Height (m)	Wave Period (s)
1	2.4	9.5
2	2.4	11.5
3	2.4	13.5
4	4.6	9.5
5	4.6	11.5
6	4.6	13.5
7	6.8	9.5
8	6.8	11.5
9	6.8	13.5

2.4 The method of wave force calculation

Under normal operation condition, the main part of the structure subjected to wave action is the lower semi-submersible cage structure. The cross section size of the bars of the cage frame is very small compared with the wave wavelength it is subjected to, which meets the requirement of D/L<0.2, and belongs to the small-scale member. Therefore, the hydrodynamic force of the structure is calculated according to Morison formula:

$$F(t)=\frac{1}{2}C_D\rho Du_x|u_x|+C_M\rho\frac{\pi D^2}{4}\frac{\partial u_x}{\partial t} \tag{1}$$

Where, C_D is the drag force coefficient; C_M is the inertial force coefficient; ρ is the density of seawater; D is the diameter of rod member; u_x is the velocity component of water quality point relative to the component axis perpendicular to the component, m/s; $|u_x|$ for its absolute value; $\frac{\partial u_x}{\partial t}$ is the acceleration component of the water quality point relative to the component perpendicular to the axis of the component, m^2/s. In this study, the drag force coefficient is 1.2 and the inertial force coefficient is 2.

3 NUMERICAL RESULTS

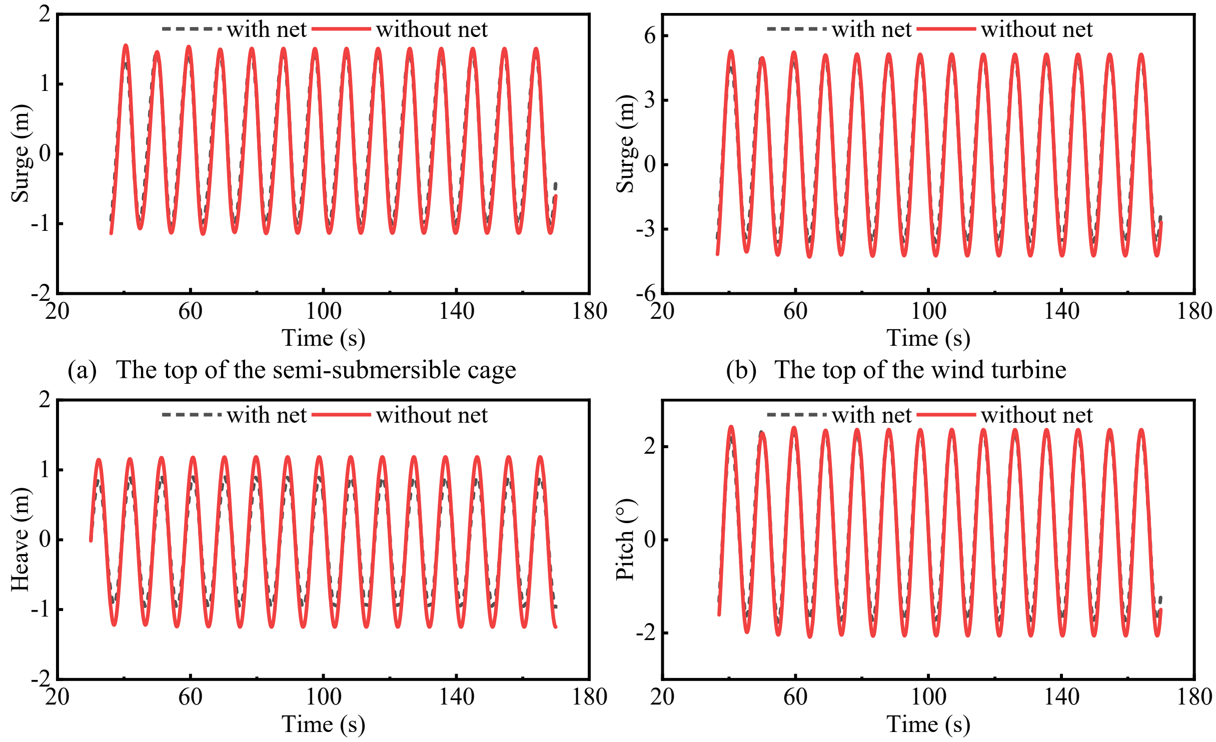
In the actual operation of the windenergie-aquaculture integrated structure, the influence of motion response is very important. Therefore, different motion response results were obtained from the measured time series of about 15 periods under different working conditions.

3.1 Motion responses

In the complex and changeable deep sea environment, the height of the wind turbine on the upper part of the wind fishing structure is close to 100 meters. Therefore, the motion response of the structure is crucial for the safety of the structure itself and the fish living in the cage. In this study, the movement of the wind turbine and the semi-submersible cage is analyzed, including heave, surge and pitch.

According to the API design specification, the platform drift distance should be less than 10% (12 m) of the water depth under the surviving sea condition. Under working sea conditions, the drift distance is less than 5-6% (6-7.2 m) of the water depth, and the heave displacement is less than 5% (6 m) of the water depth. In normal power generation, the average pitch and dynamic pitch angle of floating wind power system should be less than 5°. For the floating wind power system, if the heave movement is too large, the wind speed acting on the blade will fluctuate violently, and the fatigue damage of wind power equipment will be accelerated. If the blade moves too much with the pitch of the system, the Angle of attack of the blade will change dramatically, resulting in the violent fluctuation of the power generation.

Figure 4 shows the motion responses of the structure with net and without net at the wave condition of H = 6.8 m and T = 9.5 s. It can be observed that the motion response trend with and without net is the same, and the weight increases with net, so the motion response is smaller. Due to the larger overall size and weight of the structure, the proportion of net clothing is relatively small, and there is little difference between the motion response of the structure without net and that of the structure with net. In the surge movement, the amplitude of the movement increases with the increase of the height, and the movement is prominent at the top of the wind turbine, but all meet the specifications.



(a) The top of the semi-submersible cage (b) The top of the wind turbine

(c) The location of wind turbines (d) The windenergie-aquaculture integrated structure

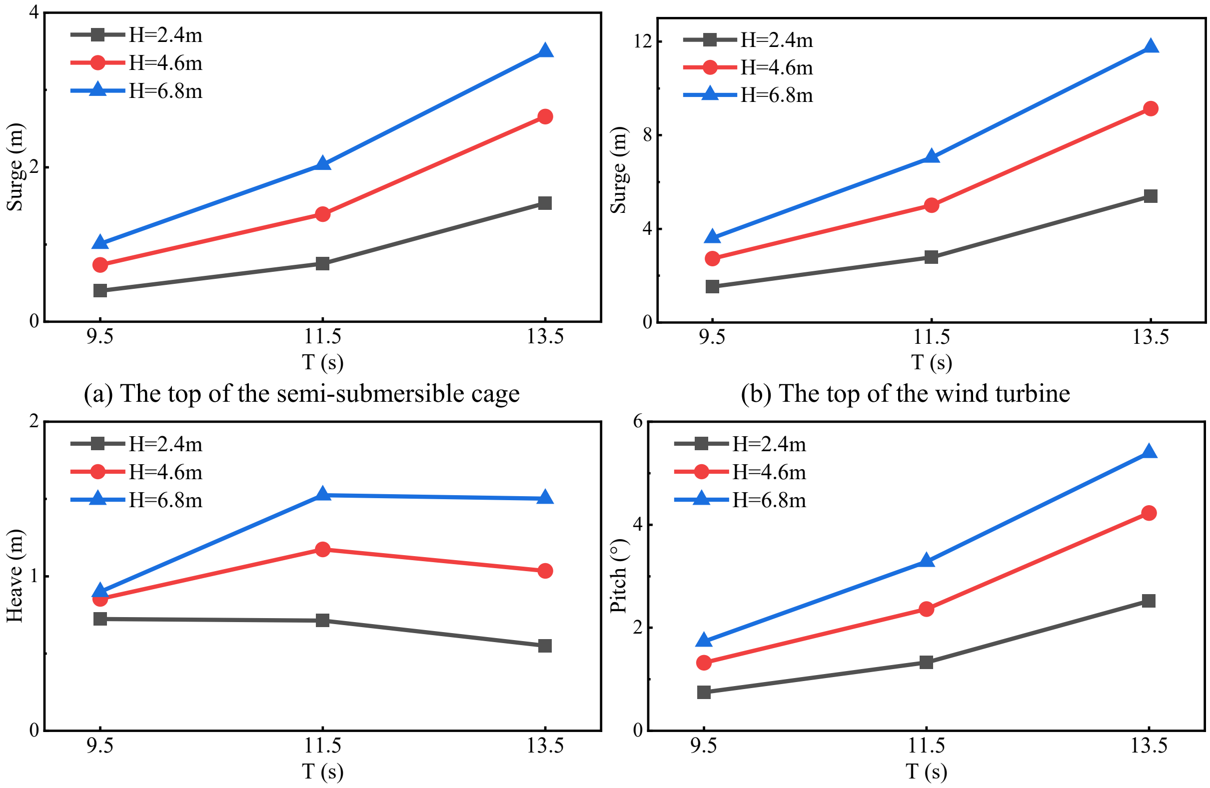
Figure 4: Time histories of the motion response of the structure (*H*=6.8m *T*=9.5s).

4. DISCUSSION

Similar to marine structures such as floating wind turbines and semi-submersible cage, the motion response of the windenergie-aquaculture integrated structure is affected by many different factors, such as the direction of wave incidence, draft, wave conditions, mooring configuration, etc. This study mainly discusses the influence of different wave conditions, wave incidence angle and net on the motion response of the integrated structure.

4.1 The effect of wave parameters

In the case of the same wave height, with the increase of the period, the response of swell and pitch motion increases. When the period is around 11.5s, the heave natural frequency of the structure reaches the maximum, so the response of motion is the most significant, as shown in Figure 5. Similarly, under the action of the same wave period, each motion response of the structure increases with the increase of wave height. In addition, under the current wave conditions, the periodic variation has a slightly greater effect on the motion response of the structure.



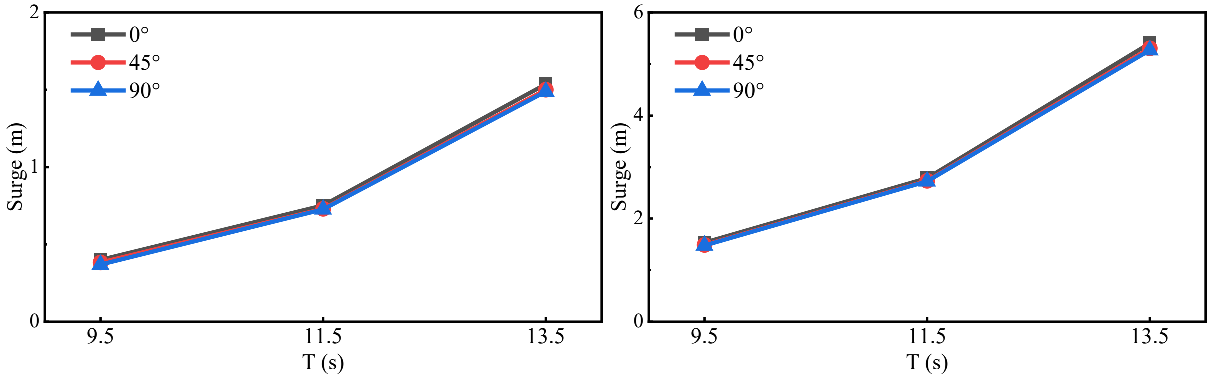
(a) The top of the semi-submersible cage (b) The top of the wind turbine

(c) The location of wind turbines (d) The windenergie-aquaculture integrated structure

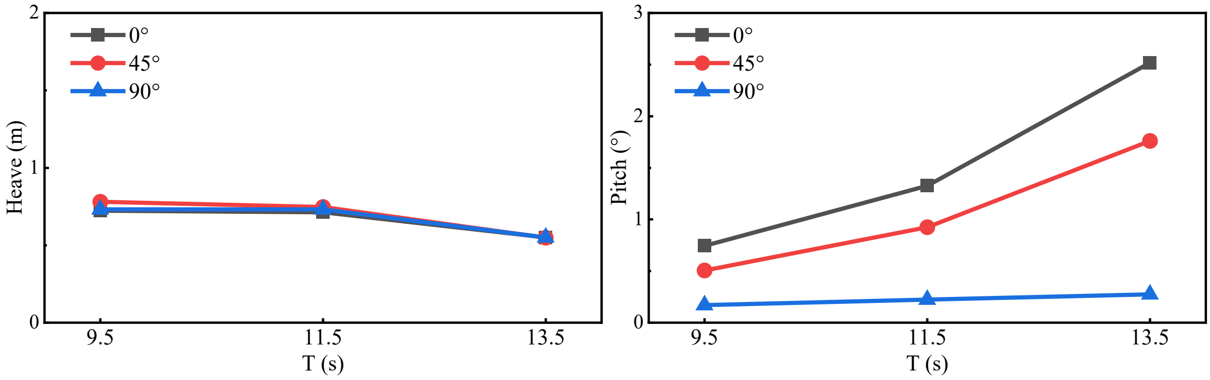
Figure 5: The motion response of the windenergie-aquaculture integrated structure varies with the period

4.2 The effect of the direction of wave incidence

In the overall structure, the two specifications of the side columns and the distribution of the inclined bracing at the top make the platform an *x*-axis symmetric structure. As shown in Figures 6, the incident waves from different directions have little influence on the surge and heave of the structure. When the wave direction is positive on the *x*-axis, the response of the structure's pitch motion is the largest, and with the increase of the period, the pitch motion is significantly enhanced. When the incident wave is 45° to the *x*-axis, the motion response is the second. When the wave is in the direction of the vertical *x*-axis, the response of the structure's pitch motion is the least, and it is greatly affected by the change of wave height.



(a) The top of the semi-submersible cage (b) The top of the wind turbine

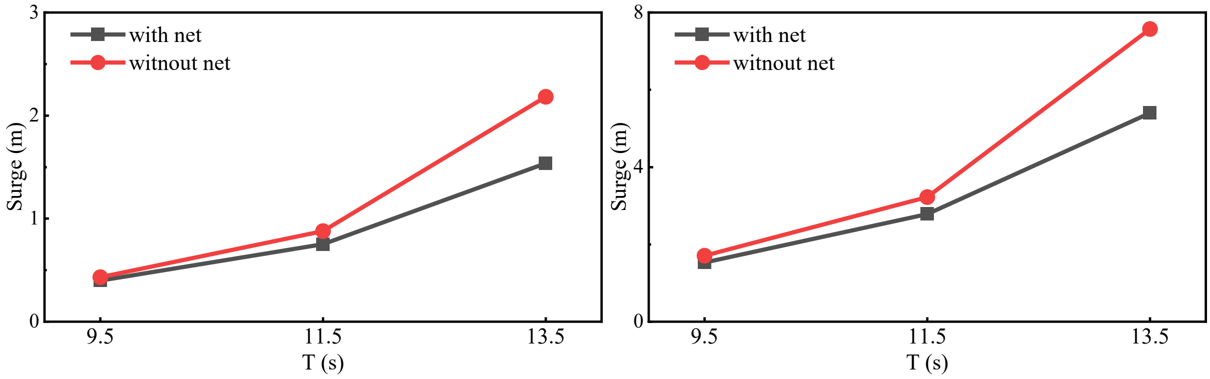


(c) The location of wind turbines (d) The windenergie-aquaculture integrated structure

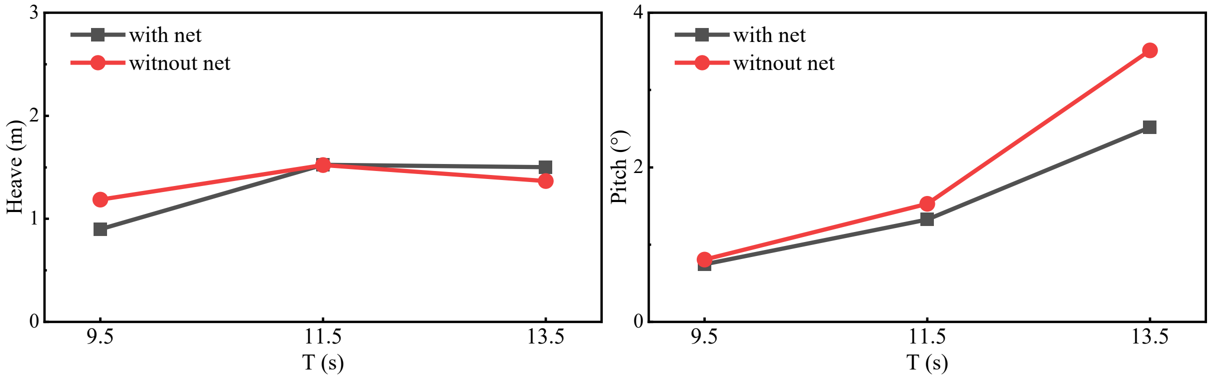
Figure 6: The motion response of the windenergie-aquaculture integrated structure varies with the period (H=2.4m)

4.3 The effect of net

The cage without net and with net has the same motion response under different wave states. Under the same wave height, the heave and pitch increase with the increase of the period, as shown in Figure 7. The maximum value of the surge movement is at the period of 11.5 s. The possible reason is that the period at this time is closer to the natural frequency of the structure, resulting in resonance.



(a) The top of the semi-submersible cage (b) The top of the wind turbine



(c) The location of wind turbines (d) The windenergie-aquaculture integrated structure

Figure 7: The motion response of the windenergie-aquaculture integrated structure varies with the period (H=2.4m)

5 CONCLUSIONS

- This paper presents a new structure which combines the floating wind turbine with the semi-submersible aquaculture cage. The finite element model was established to simulate the dynamic response of the model from three representative wave conditions (small wave, medium wave and large wave) and three wave directions (0°, 45° and 90°). The following conclusions are drawn from the comparative analysis.

(i) Surge and pitch of the model increase with the increase of the wave height and period, and surge reaches its maximum when the period is T=11.5 s (f=0.087 Hz, which is the natural frequency of the structure). In practical engineering, the natural frequency of the model should be avoided to be consistent with or close to the frequency of the normal wave.

(ii) Under different wave incidence angles, the motion responses of pitch and heave are basically the same. With the increase of wave height and period, the surge, heave and pitch all increase and are more obviously affected by the period. It is concluded that the pitch reaches its maximum value at 0° wave incidence angle. In practical engineering, more attention should be paid to the arrangement of the structure and the direction of normal waves to ensure the stability of the structure.

ACKNOWLEDGEMENTS

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