



Article Mooring Stability Study for Novel Wave Energy Converter Based on Regular Wave

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Abstract: The mooring system not only plays a vital role in keeping wave energy generators floating stably, but also affects the success of engineering design. Combining wave force theory and the hydrological data obtained from the field measurements of a certain sea area in the Bohai Sea, the Stokes second-order wave theory was adopted to design the mooring system of a new type of power-generating device. At the same time, the study uses the Aqwa software to gather the dynamic data of a power-generating device in a real test, and then makes models and carries out regular wave tests so as to verify the viability of the mooring system and the stability of the whole power-generating device. All of this work will provide a theoretical basis for the manufacture of an engineering prototype and its reliable supply of power.

Keywords: wave force; horizontal axis rotor; mooring system; hydrodynamic response

1. Introduction

Currently, China accounts for about one-fifth of the world's total energy consumption, becoming the largest energy consumer in the world. With the continuous advance of industrialization, China's energy consumption is projected to increase by 60% by the year 2030. Thus, China's policy on energy consumption is bound to influence the energy consumption trends in the whole world. New and green energy such as wind energy, solar energy, marine energy, and other types of renewable energy are progressively being promoted by China's government. The application of new energy has exerted an important influence in the country's adjustment of its industrial structure, the fostering of emerging industries, and reform of its energy structure [1-4]. Over the past decades, the US, South Korea, the EU, and other countries and regional organizations have successively formulated schemes on exploring marine renewable energy [5,6]. The Chinese government has also organized the detailed strategic deployment of marine renewable energy, implemented relevant plans, and funded the research, development, and deployment of MRE. Abundant in marine resources, China has much marine renewable energy to be explored in the Bohai Sea and the sea areas of its eastern and southern parts [7–9]. As one of the most promising types of marine energy, wave energy has also been developed enormously. China's research on wave energy converters began at the end of the 1970s, the time when only a few science and research institutions were carrying out studies in the field. At present, the situation has changed greatly. Apart from the support of policies and finance from the central and local governments, many research institutions, colleges and universities, and enterprises have all carried out a large number of research projects related to marine renewable energy. Moreover, some experiment devices and engineering prototypes have been set up in succession, and many of them have been tested at sea [10–12].



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In recent years, the utilization of wave energy has become the hot topic in new energy that coastal countries in the world have focused on. The power-generating device of the horizontal axis rotor is relatively mature in the application of tidal current energy. Industrial groups and power companies in France have employed the OpenHydro turbine technology to build up the first exemplary tidal current turbines. The 150 kw ORPC OCGen®power system that MRE companies in the US developed has also been put into commercial use. Both devices use the horizontal axis rotor to transport the driving force of the impeller to power devices in order to generate electricity [13]. The Korea Maritime and Ocean University developed a floating horizontal axis wave energy model device. It mainly uses the rise and fall of flanked water that follows the movement of the wave to propel the turbine to rotate, and then transports the driving force to power devices through the force transmitter. An engineering prototype of the device has not yet been created [14]. Wuhan University and the Chinese Academy of Sciences jointly developed a 1 kw vertical axis tidal current energy generating device and performed marine experiments in the sea area of Zhuhai. Shanghai Ocean University designed a horizontal axis generating device and conducted a series of experiments in the sea areas of Xiamen [15].

In order to satisfy the progressively rising power demand of China's coastal sea areas and remote islands, the marine ranch's needs for new energy, and in order to make more efficient use of marine energy, a new type of horizontal axis rotor direct-drive wave energy generating device has been designed. The device has a capacity of 1.1 kw and weighs about 28 tons, and it has been tested in the Chengshantou sea area in Weihai, Shandong province(see Figure 1) [16]. The principle of power generation is shown in Figure 2 [17]. It forms a closed body of water through the entry and exit passage of the cross-flow turbine. As a result of the strike and backflow of the wave, the water body in the passage flows back and forth, and then drives the rotor in the passage to rotate in one direction to make the direct-drive generator produce electricity. The main feature of the device is its direct transformation of wave energy into electricity, which will maximize the efficiency of transformation. The device can float on the surface of the sea by means of four mooring points. Thus, the mooring system is a crucial element that will affect the stability of power generation. However, research on the mooring systems of wave energy generating devices is rare at present. Based on the hydrological data from the new generating devices working in the sea area, the study will simulate the feasibility and stability of a four-point mooring system and verify this through a regular wave test in order to provide a theoretical basis for the manufacture of a power-generating prototype and its reliable supply of power.



Figure 1. Engineering prototype at the sea trial test.



Figure 2. Principle of power generation.

2. The Frequency Domain Analysis of Device

The frequency domain analysis employs frequency response to analyze the response characteristics of the floating body under the effect of wave force. After having studied the effect of viscous force on the floating body, Lopes found that the acting force that the viscous force—in contrast with wave force and the power take off system—has applied to the floating body can be negligible [18–20]. The research carried out by Muliawan and Vicente indicates that the force produced by relaxed moorings hardly affects the way the floating body absorbs the energy of the wave [21]. The proper choice of wave theory is not only the key to calculating the mooring's force response, but also the crucial factor that involves the success of the engineering design. Current studies on the widely applied wave theories have shifted from regular wave to irregular wave. In 1887, Stokes, a British expert on hydromechanics, put forward the Stokes wave theory. Advanced Stokes wave theory is often used in the calculation of maximum wave in terms of offshore construction. However, the Stokes wave theory fails to take the effect of changes in water depth into account, so it is exclusively applicable to the average depth of water.

The experiment on the engineering prototype was carried out in a certain sea area of the Bohai Sea. According to the wave data of the sea areas neighboring Weihai in the year 2016, 2017, and 2018 in the Monthly Report of China's Offshore Marine Climate Monitoring provided by the National Marine Environmental Forecasting Center, the average wave height of the sea area during the three years was 0.75 m, and the average cycle was 3.9 s. Additionally, the water depth of the place where the generating device was tested stood at 15 m. The statistics showed that the wave height ranged from 0.5 m to 1.0 m during the three years, while the cycle ranged from 3.4 s to 4.4 s. Thus, the length of the wave was $L = \frac{gT^2}{2\pi} \approx 23.76$ m, and the wave number was $k = \frac{2\pi}{L} \approx 0.26$, $\frac{d}{L} = \frac{15}{23.76} \approx 0.63 > 0.5$. According to the Le Mehaute theory, the two dimensionless parameters have a horizontal coordinate $\frac{d}{gT^2} \approx 0.10$ and a vertical coordinate $\frac{H}{gT^2} \approx 0.005$. The Stokes second-order wave theory is applied theoretically to the tested sea area [22,23].

In terms of the horizontal axis rotor wave energy generating device, based on the hydrological data, the study selected the optimal wave theory that matched the concerned engineering project, conducted experiments, and analyzed the floating stability of the device with moorings. As a critical component of the wave energy generating device, the mooring system acts as the basis for the stable functioning of a generating device, the effect of which will influence the entire operation of power generators. The study conducted simulations to analyze the limiting effect of the mooring system on the floating body so as to ensure that the floating body can produce stable electricity. To reduce statistical errors, the catenary mooring method was adopted to simulate numerical values, and then the experiment was conducted to confirm the moving trajectory of the floating body [24–27].

In order to ensure the stability of the device, a four-point mooring method was adopted. That is, four identical gearless anchor chains were used, with the angles between neighboring chains being 90° . The arrangement of chains are shown in Figure 3. The device floats on the sea, and the damping plate under the device connects to the bottom of the sea through anchor chains to ensure the stability and balance of the device when wind wave flows strike it. The water depth of the area where the device is placed is 15 m, and the device 's draft is 4.7 m; thus, the vertical length of the anchor chains is 10.3 m. The weight of the chains is 7/8 of their weight in a vertical position. There are four anchor chains, a chain's diameter is 50 mm and its weight is 49.5 kg/m; therefore, the total weight of the chains is 2040 kg, and their weight in the water is about 1759 kg when the buoyant force is excluded [28–30].



Figure 3. A schematic diagram of the catenary mooring method.

Dangling chain length:

$$S_{h} = \sqrt{\frac{2HT_{0}}{q_{w}} + H^{2}} \tag{1}$$

In the equation above, H refers to the vertical distance from the ground of the anchor point to the anchor hole; T_0 is the tension at the ground end of the hanging chain; q_w represents the wet weight of the anchor chain per unit length in water.

$$\Gamma_0 = P_a + P_w \tag{2}$$

In the equation above, P_a stands for the acting force of wind applied to the device; P_w refers to the acting force of water flows applied to the device.

$$P_{a} = \frac{1}{2}\rho_{a}C_{a}V_{a}^{2}\left(A_{a}\cos^{2}\theta + B_{a}\sin^{2}\theta\right)$$
(3)

In the equation above, ρ_a represents the density of the air, which is 1.25 kg/m³; C_a is the wind factor, at 0.70~0.95; Va refers to the relative wind speed; A_a stands for the area of the device above the waterline; B_a represents the flank area of the device above the waterline; θ is the wind's chord angle.

$$P_{w} = f \cdot \Omega \cdot V_{w}^{1.83} \tag{4}$$

The equation above is the Froude formula. Here, f represents the water's friction coefficient, f = 0.17; V_w stands for the speed of water flows; Ω is the wet surface area of the device below the waterline.

The length of anchor chains in the water is calculated as follows:

$$S_{b} = \frac{1}{2}S_{h}$$
(5)

The total length of anchor chains is obtained with the following equation:

$$S = S_h + S_b = 1.5S_h \tag{6}$$

The AQWA software was used to carry out a coupling simulation analysis of the device when the wind, wave, and flows were in the same direction; the following data were obtained: the total length of the single anchor chain was 23.13 m, the cycle of the wave was at 3.9 s, the height of the wave was 0.75 m, the speed of the wind was 6 m/s, and the water flow velocity was 2 m/s. The value of the response amplitude operators, or the RAO in the X, Y, and Z directions varied with the wave frequency, which is shown in Figure 4. Likewise, the value of the RAO in the RX, RY, and RZ directions varied with the wave frequency, which is shown in Figure 5.



Figure 4. The way the value of the RAO in the X, Y, and Z directions varied with wave frequency.



Figure 5. The way the value of the RAO in the RX, RY, and RZ directions varied with wave frequency.

As is shown in Figure 4, when the device is installed at 90 degrees, the value of the RAO in the X direction barely varies with the increase of wave frequency. The value of the RAO in the Y direction firstly rises and then falls as wave frequency increases, and it reaches the maximum value when the frequency is around 0.33 Hz; the wave cycle is at 3 s. The value of the RAO in the Z direction falls gradually with the rise of wave frequency. When the wave frequency approximates 1 Hz, the value of the RAO of the device is roughly equivalent to zero, and the device fails to synchronize with the wave frequency due to the effect of inertia.

As is shown in Figure 5, when the device is installed at a 90-degree angle, the value of the RAO in the RX direction varies greatly with the increase of wave frequency, and it reaches the maximum value when the frequency is about 0.13 Hz, which indicates that the device moves greatly in the RX direction. The value of the RAO in the RY and RZ directions barely varies with the increase of wave frequency.

3. Regular Wave Simulation

Based on the state of the sea in the experimental marine area, three working conditions with regular wave are simulated to obtain the movement changes of the device in a state of stability so as to determine the rationality of the mooring system design, as is shown in Table 1.

Wave Element Working Conditions	Prototype Value		Model Value	
	Wave Height H (m)	Cycle T (s)	Wave Height H (m)	Cycle T (s)
Case 1	0.7	3.6	0.07	1.15
Case 2	0.8	3.6	0.08	1.15
Case 3	0.9	3.6	0.09	1.15

 Table 1. Regular wave working conditions chart.

According to the actual state of the sea, the movement of the device becomes stable after 25 s, so the simulation selects a 120-s movement for the device and makes a comparison with the experimental data under three working conditions.

As we can see in Figure 3, in the regular wave simulation, the device is set to face the wave at 90°. In Figures 6–8, we can see that the device drifts with the tide for some time at first, and then becomes stable after 25 s with the tension of the mooring system, while its rotation in the RX, RY, and RZ directions also gradually plateaus. As the wave height increases, the angles of RX and RY barely change. That is, the angles of the roll and pitch barely change. The angle of the RZ or yaw begins to grow under the third working condition, and then hovers around plus or minus 18 degrees. Thus, the yaw's angle gradually becomes large in the same cycle as wave height changes.







Figure 7. The movement duration of the device in the RX, RY, and RZ directions under the second working condition.



Figure 8. The movement duration of the device in the RX, RY, and RZ directions under the third working condition.

4. Mooring Stability Experiment

4.1. Model Experiment

Based on the principle of resemblance and in view of the fundamentals of engineering construction and the condition of the water trough, the tested model was built at a scale of 1:10, and the design of anchor chains was made to resemble the prototype in length, mass, and elasticity. The test of the model was carried out in the wave–current coupling water trough of the National Engineering Laboratory. The installation of the model is shown in Figure 9. The facilities and instruments employed in the experiment include the motion alignment tool, tension sensor, mooring lines, wave height recorder, and current meter. The motion alignment tool was installed before placing the model in the water for testing. The parameters of the model such as its center of gravity, the depth of draught, and the rotary inertia through ballast lead or iron were subsequently adjusted. In view of the wave mass and current reflex caused by the current flowing through the water trough, the model was placed as far as possible, near the center of the water trough. The distance between the model and the wall of the water trough was about 1.7 m, much larger than the diameter of the model; thus, the effect of the wall can be excluded. The experiment is shown in Figure 10.



Tension Sens

Figure 9. Model's installation location.



Figure 10. The wave energy extraction system in an experimental flume.

4.2. Analysis of Experiment Results

The change of the shaking angle is taken as an absolute value. As shown in Figures 11–13, the statistics of the test in the water trough reflects the model's angle variations in the RX, RY, and RZ directions under different working conditions. The model selects 25 s of experimental time. The model oscillates irregularly before 10 s due to the influence of wave flow, but after 10 s, the model gradually becomes stable on the whole.



Figure 11. Test under the first working condition.



Figure 12. Test under the second working condition.



Figure 13. Test under the third working condition.

The comparison of the experimental results under three different working conditions reveals that the model's rotary angle hardly varies in the RX direction when the cycle remains unchanged and the wave height increases. That is, the roll's change always stays within an angle of plus or minus 3 degrees. Such a slight change barely affects the generating stability of the whole device, which will enable the device to absorb the uttermost energy produced by the wave current. The model's rotary angles in the RY and RZ directions, namely the angles of pitch and yaw, both change within an angle of

plus or minus 15 degrees, the effect of which on the whole operation of the device is relatively small.

5. Conclusions

In this study, the mooring system of the power-generating device was designed, and the mooring angle was determined by calculation. After simulating the wind, wave, and current coupling of the power-generating device, the angle changes of the device under three different working conditions were obtained. At the same time, a series of experiments were carried out in the sink and the following conclusions were obtained:

Under the same working conditions, a comparison of the simulation and experimental results shows that due to the lack of airflow equipment, the angle of change in the experiment is about 2 degrees smaller than that in the simulation, but the overall curve of the experiment and the simulation is the same, which has reference value.

Both simulation and experimental results show that under regular wave conditions, when the period remains the same and the wave height increases, the roll angle change is stable within plus or minus 3 degrees.

This design of the mooring system can ensure the stability of the device, thereby absorbing the most extreme wave energy.

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