Design of Hydraulic Power Take-off for Wave Energy Converter on Artificial Breakwater

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***Abstract*— With the increasing use of the present social resources, fossil energy resource is at risk. So it's imperative to tap the renewable resource. The ocean resource is a kind of reproducible green resource. Oscillating-buoy becomes a main kind of wave energy converter (WEC) which could extract wave energy from its oscillating motion. In this paper，a hydraulic power take-off device for oscillating buoy wave energy converter on artificial breakwater is designed, the hydrodynamic analysis of the oscillating-buoy is performed with ANSYS-AQWA, including added mass and radiation damping coefficient. The mathematical model of linear PTO is established and simulated with SIMULINK to get the power generating ability of the oscillating-buoy with the linear PTO. In addition, a hydraulic PTO system is designed and the its dynamics is simulated with AMESim. Finally, the control strategy of constrained motion of PTO is proposed to ensure safe operation under high sea states.**

***Keywords*—Artificial breakwater; Wave energy converter; Hydraulic power take-off; Linear generator; Constrained motion**

I. INTRODUCTION

With the development of science and technology, people's demand for energy is increasing. Because of limited reserves and non-renewability, fossil energy such as coal, petroleum, and natural gas cannot meet the requirements. Moreover, during the exploitation and use of fossil energy resources, it causes pollution and damage to the ecological environment. For example, carbon dioxide generated during the combustion process is the prime culprit for global warming and the green-house effect.

In order to convert wave energy into electricity, a WEC device must have a power extraction device (PTO) [1]. The PTO system should work properly under harsh sea conditions. There are some kinds of WEC, such as point absorption, pressure difference, attenuation, termination, shock water column. The type of PTO mainly include turbines, linear generators, and hydraulic units [2].

An oscillating buoy wave hydraulic PTO device on the artificial breakwater is designed in this paper. It can effectively convert ocean wave energy into electrical energy. Hydraulic transmission is characterized by its flexible transmission, energy storage and voltage regulation, which guarantees stable energy transmission and utilization of wave energy. The WEC is designed and a linear PTO model is established with frequency domain analysis. The effect of system damping on linear PTO is summarized. After that, a model of hydraulic PTO is established, and a hydraulic rectifying circuit is added so that the hydraulic oil passed through the hydraulic motor in a single direction to ensure the stable operation of the generator. Finally, by analyzing the simulation results of the linear PTO and the hydraulic PTO under different damping conditions, the optimal damping control strategy is carried out to ensure safe operation under high sea states.

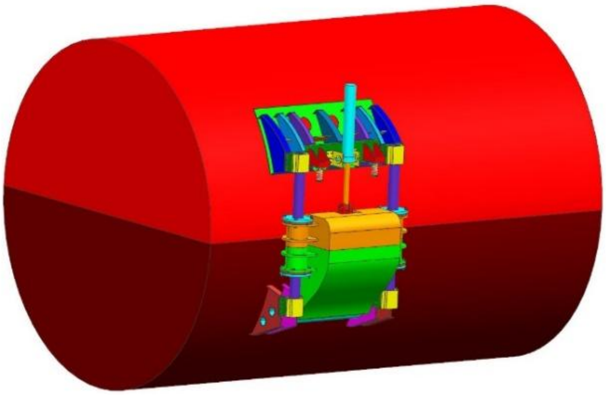

Fig. 1 The wave energy converter model on artificial breakwater

II. THE DESIGN OF WEC

The wave energy conversion device based on the artificial breakwater is shown in Fig. 1. The WEC is placed on a artificial breakwater, the design power of the WEC is 3kW under the condition of the significant wave height of 2m, and the motion stroke of the buoy is restricted to ±0.5m. The size of the float is 2.0m×1.2m×0.7m. An hydraulic cylinder is connected to the WEC for transmitting wave energy to the hydraulic PTO.

The WEC mainly includes the following three parts:

A. The mechanical supporting structure is used to fix the wave energy conversion device on the artificial breakwater.

B. The buoy, which is placed on the slide rail, oscillating vertically with the sea wave to convert the wave energy to the mechanical energy of the buoy.

C. Hydraulic cylinder, mainly used to connect hydraulic PTO system.

In addition, mechanical limit structure is added for safety under harsh sea condition.

III. FREQUENCY DOMAIN ANALYSIS FOR WEC

Based on the linear wave theory, the following assumptions are taken. Waves are two dimensional. The fluid is incompressible and no viscous losses. There is no underlying current. Wave height is much smaller than the water depth and the wave length.

Referring to Jeffreys [3] and Falnes [4], the hydrodynamic model for the WEC is built using linear wave theory in the frequency and time domain. The float that moves with wave in the sea has six degrees of freedom, heave, surge, sway, pitch, roll and yaw [5]. However, for simplicity, only one the heave motion of the buoy is used to convert wave energy (vertical to the sea surface x, x = 0 means the static sea surface). The control equation for the buoy is

$$m\ddot{x}=f_h(t)+f_m(t) \tag{1}$$

Where m is the mass of the buoy, $\ddot{x}$ is the acceleration of the buoy, $f_h(t)$ is the wave force, and $f_m(t)$ is the mechanical force generated by the PTO system. The wave force is

$$f_h(t)=f_e(t)+f_r(t)+f_{hs}(t) \tag{2}$$

Where $f_e(t)$ is the wave excitation force, $f_r(t)$ is the radiation force, $f_{hs}(t)$ is the hydrostatic buoyancy force, which is linearized to obtain the linearized hydrostatic force.

$$f_{hs}(t)=-\rho gSx \tag{3}$$

Where ρ is the density of sea water,1.025g/cm^3, g is the gravitational acceleration 9.8m/s^2, S is the cross-sectional area of the buoy in contact with the surface of the water in heave motion, 2.4 m^2.

When the input waveform is an ideal sine wave, the harmonic function of the excitation force can be written as

$$f_e(t)=\mathrm{Re}(F_e e^{j\omega t}) \tag{4}$$

Where $f_e(t)$ is the amplitude of the excitation force, and the excitation force is the sum of the incident wave and the diffracted wave component. Since the system is linear and has only one degree of freedom, the amplitude of the excitation force is proportional to the height of the wave [6]

$$|F_e|=\Gamma(\omega)\frac{H}{2} \tag{5}$$

Where H is the wave height, 2 m. $\Gamma(\omega)$ is the positive real force coefficient that determined by the wave frequency and the shape of the buoy.

$$\Gamma(\omega)=\sqrt{\frac{2g^3\rho B(\omega)}{\omega^3}} \tag{6}$$

Where $B(\omega)$ is the radiation damping coefficient, which is related to the frequency of the wave and the shape of the buoy. ω is the frequency of the wave.

Assuming that the complex amplitude of the radiation force is proportional to the complex amplitude of the buoy motion,

$$F_r=G(j\omega)X(j\omega) \tag{7}$$

Where the radiation force is

$$f_r(t)=\mathrm{Re}(F_r e^{j\omega t}) \tag{8}$$

Displacement is

$$x(t)=\mathrm{Re}(Xe^{j\omega t}) \tag{9}$$

The radiation force is decomposed in phase with the acceleration and velocity of the buoy [7]. So

$$G(j\omega)=\omega^2 A(\omega)-j\omega B(\omega) \tag{10}$$

$$f_r(t)=-A(\omega)\ddot{x}-B(\omega)\dot{x} \tag{11}$$

The coefficient $A(\omega)$ is the additional mass and $B(\omega)$ is the radiation damping coefficient, both of them depend on the shape of the buoy and the wave frequency.

Therefore, by collating the above formula, the following expression can be obtained for solving the buoy motion amplitude in regular wave.

$$(m+A)\ddot{x}+B\dot{x}+\rho gSx=F_e e^{j\omega t}+f_m \tag{12}$$

The ANSYS-AQWA software is used to calculate the additional mass $A(\omega)$ and the radiation damping coefficient $B(\omega)$ for the designed buoy. The mesh model of the buoy mesh is shown in Fig.2. The node number is 31246 and the element number is 31244. According to the centre of gravity, moment of inertia, quality parameters, the additional mass $A(\omega)$ of buoy is shown in Fig.3, radiation damping coefficient $B(\omega)$ is shown in Fig.4. The buoy additional mass is 1298 kg, and radiation damping is 0.119N/(mm/s) with the sea wave of 8s period.

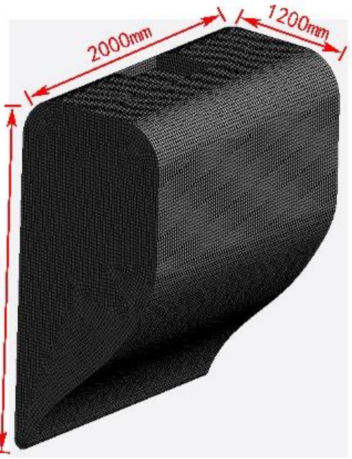

Fig. 2 The buoy shape and model mesh

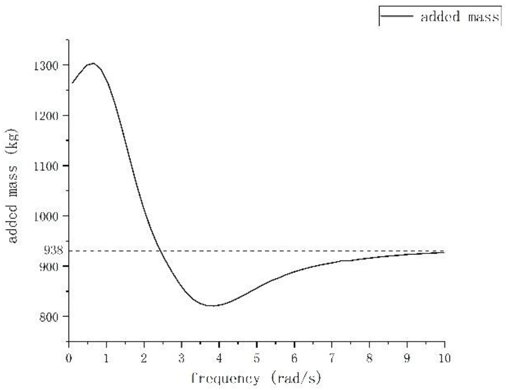

Fig. 3 The added mass of the buoy

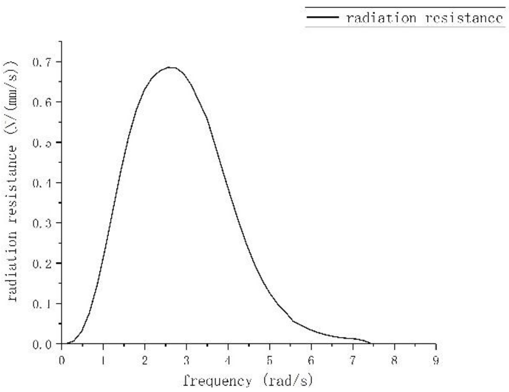

Fig. 4 The radiation resistance of the buoy

IV. MODELLING AND SIMULATION OF LINEAR PTO

The mechanical force that acts on the PTO is expressed as,

$$f_m(t) = -Kx - C\dot{x} \tag{13}$$

Where K is the spring stiffness and C is the damping coefficient. The motion equation of the linear PTO system is obtained,

$$(m+A)\ddot{x} + (B+C)\dot{x} + (\rho gS + K)x = f_e(t) \tag{14}$$

Taking the Laplace transform,

$$\frac{X(s)}{F_e(s)} = \frac{1}{(m+A)s^2 + (B+C)s + (\rho gS + K)} \tag{15}$$

Convert the equation (15) to the frequency domain,

$$X(j\omega) = \frac{F_e(j\omega)}{-\omega^2(m+A) + j\omega(B+C) + (\rho gS + K)} \tag{16}$$

The velocity is

$$U(j\omega) = \frac{F_e(j\omega)}{j\omega(m+A) + (B+C) + (\dfrac{\rho gS + K}{j\omega})} \tag{17}$$

For the designed linear PTO, which oscillates in the wave of 2m height and 8s period, setting the damping coefficient C to 50kNs/m and spring coefficient K to 0, the simulation results for Wave and WEC displacement, PTO Force and PTO Power are shown in Fig.5.

By changing the damping C of the linear PTO from 0-200 kNs/m, the WEC displacement, PTO force and power are shown in Fig.6, Fig.7 and Fig.8 respectively .

Fig.6 shows that, when the motion stroke of the buoy is restricted to ±0.5m, the motion stroke of the buoy decreases with the increase of the damping coefficient exponentially.

Fig.7 shows that, the PTO force increases with the damping coefficient. When the damping coefficient is about 100 kNs/m, the PTO force tends to constant.

From Fig.6 and Fig.8, it can be concluded that, under the constrained motion stroke of the buoy, to realize the design power of 3kW for the WEC, the damping coefficient must be controlled between 50 and 170 kNs/m.

V. MODELING AND SIMULATION FOR HYDRAULIC PTO

The hydraulic PTO for WEC has the properties of working with high-force waves of low frequency, and the power generation elements of the hydraulic PTO is smaller in size, cheaper, compared to the electrical one [9].

Based on the analysis of linear PTO system, it shows that, the working pressure of the hydraulic cylinder in the PTO can be used to adjust the damping coefficient of the PTO. And the working pressure of the hydraulic cylinder is controlled by hydraulic motor and accumulators.

The hydraulic PTO system is simulated with Amesim. The hydraulic circuit mainly includes a hydraulic cylinder for connecting the buoy with the hydraulic PTO, a rectifying circuit that let the hydraulic oil always pass through the hydraulic motor in the same direction, the high and low accumulators are used to provide a stable pressure difference and stabilize the loop pressure to ensure the stability of the working oil pressure for the hydraulic motor, a charge oil

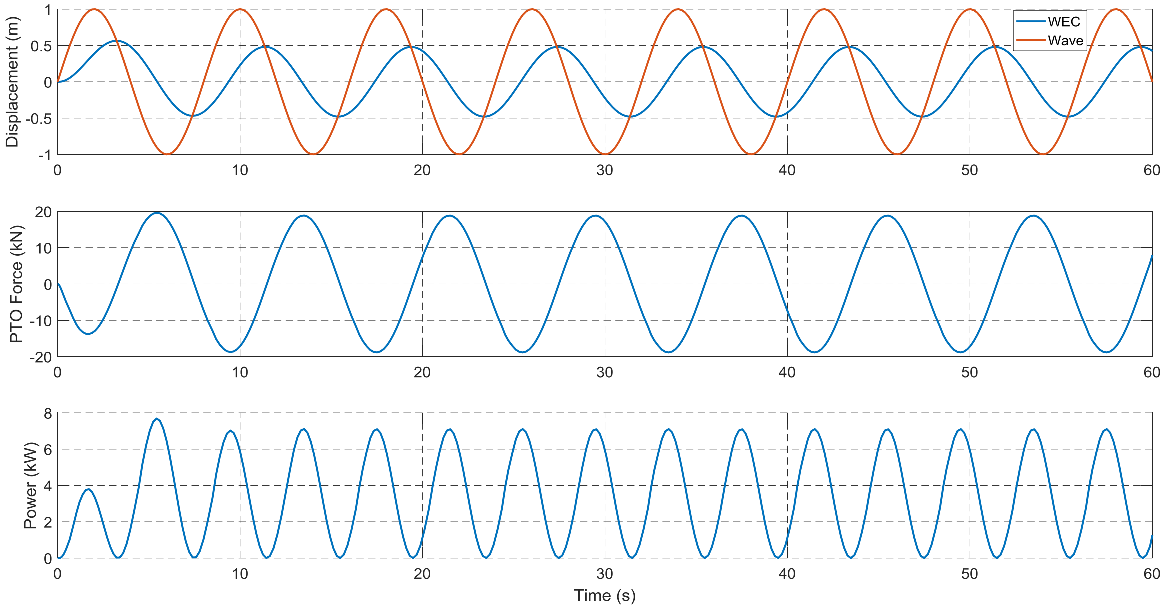

Fig. 5 Top:Wave and WEC displacement, Middle: PTO Force, Bottom: PTO Power for linear PTO characteristics C = 50kNs/m

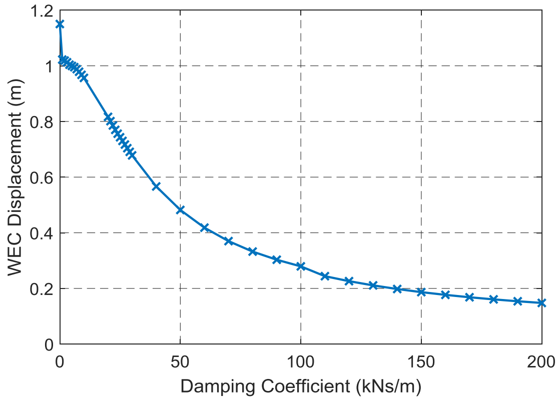

Fig. 6 WEC Displacement in different damping coefficient

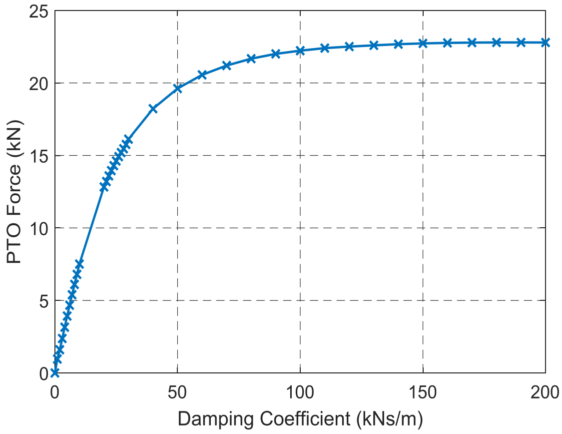

Fig. 7 PTO Force in different damping coefficient

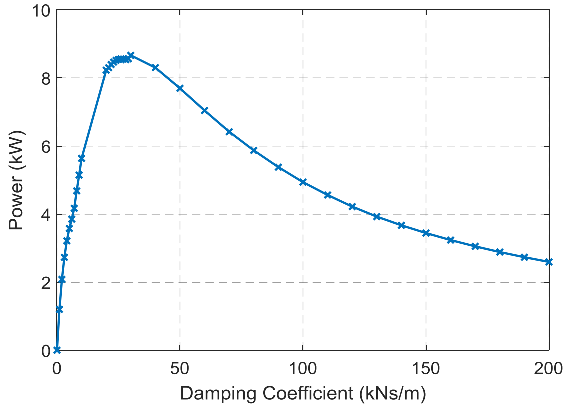

Fig. 8 Power in different damping coefficient

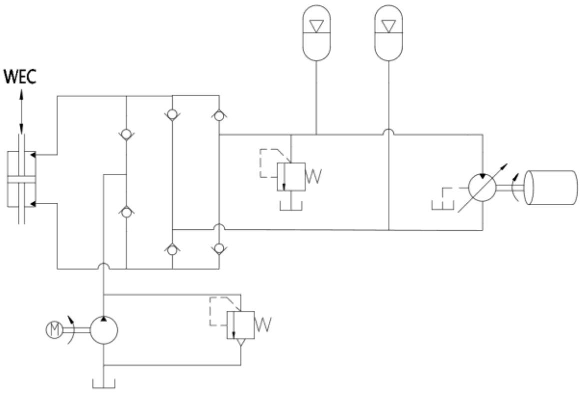

Fig. 9 hydraulic PTO unit circuit diagram

booster device is used to ensure the minimum hydraulic pressure in the hydraulic circuit for the sake of leakage, etc., an variable displacement motor is used to drive the generator for power conversion. The hydraulic PTO unit circuit is shown in Fig.9. The inner diameter of the hydraulic cylinder is 0.16m, and the diameter of the piston rod is 0.11m. In order to obtain uniform power generation, a double-acting double-rod hydraulic cylinder is used.

In the hydraulic PTO system, the safety valve, which is a protective device, is used and set to 350 bar to prevent dangerous high pressure for the hydraulic system. In addition, the main working principle of the charge booster device in the PTO system is to add a pair of check valves to the system and set the rated pressure of the overflow valve to 10 bar. When the minimum pressure of the PTO system is higher than 10bar, the oil through the overflow valve passes by booster pump and returns to the tank without entering the system; when the system minimum pressure is below 10 bar, the overflow valve closes and the booster pump pumps the hydraulic fluid through the check valve into the system to a pre-set pressure of 10 bar.

According to the hydraulic circuit diagram, the PTO force is

$$f_{PTO} = (p_1 - p_2)A_p \tag{18}$$

Where, p_1, p_2 is the piston chamber pressure on the two sides of the hydraulic cylinder, A_p is the area of the piston, which is $0.0236m^2$ and f_{PTO} is the PTO force that acts on the piston rod, which value corresponds to f_m in equation (13).

The captured power of the PTO system is

$$P_{cap} = f_{PTO}\dot{x} \tag{19}$$

The generated power of the PTO system is

$$P_{gen} = T_m \omega_m \tag{20}$$

Where ω_m is the rotating speed and T_m is the torque of the hydraulic motor, which is calculated as

$$T_m = (p_A - p_B)D_m \tag{21}$$

High and low accumulator pressures p_A and p_B is 30 and 10bar respectively, and D_m are hydraulic motor displacement, 160ml/r. In addition, the one-way valve opening pressure is 0.2bar and the maximum flow rate is 400l/min.

The efficiency of PTO system is

$$\eta_{PTO} = \frac{P_{gen}}{P_{cap}} \tag{22}$$

The external force of ±30kN is acted on the WEC for simulation. The total WEC mass is calculated by the sum of the buoy mass and additional mass, which is 4186kg, and the radiation damping added to the hydrodynamic analysis is 0.119N/(mm/s). The simulation results are shown in Fig.10, Fig.11 and Fig. 12.

According to the simulation, the hydraulic PTO efficiency tends to be 0.8 when the external force is ±30kN, which is mainly due to the friction and loss force factors in the simulation, including the friction force of the hydraulic cylinder is 1kN/(m/s), and the Coulomb friction force is 2100N. In addition, the diameter of the pipe is 20mm, and the wall thickness is 2.75mm. The overall length is about 10m. When the system is stable, the PTO capture power is 3.4kW, and the WEC displacement is kept within 1m, that is, it moves within ±0.5m. The hydraulic system meets the design requirements.

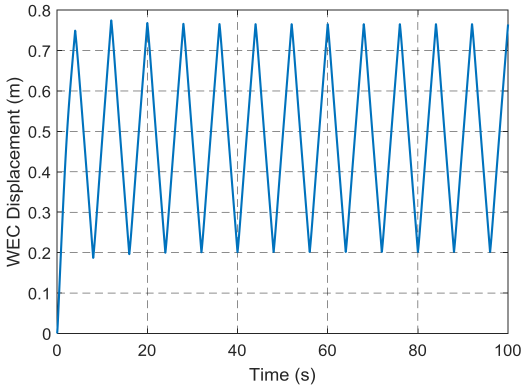

Fig. 10 WEC Displacement

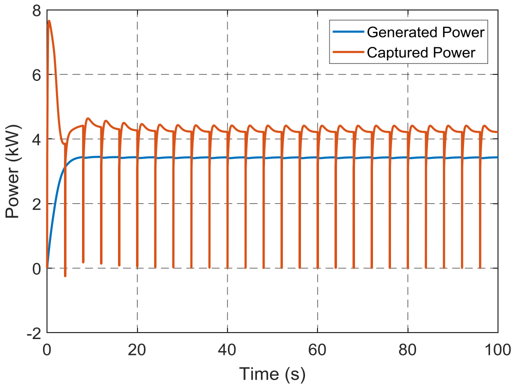

Fig. 11 PTO captured and generated power

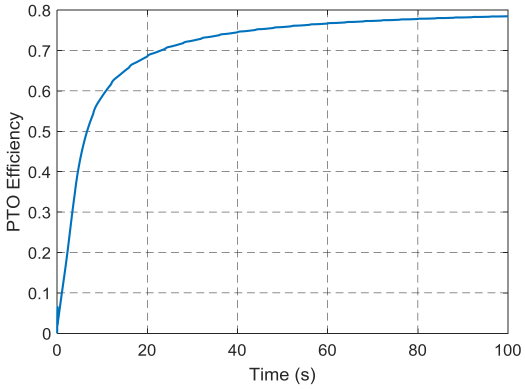

Fig. 12 PTO efficiency

VI. Constrained Motion Control Strategy

Since the WEC is operated in the sea, it's operation will be affected by extreme weather. In order to ensure that the WEC operates normally and not be damaged in harsh conditions, the motion constraint control strategy is added. On the one hand, the motion constraint control strategy can ensure that hydraulic PTO hydraulic cylinders work within a certain stroke. On the other hand, it can ensure that the entire system will not be damaged in harsh conditions.

By adding a limiting structure to prevent the buoy from over-traveling and damaging the WEC. From Fig.6, 7 and 8, it can be concluded that both the maximum power and the displacement of the WEC can be limited by changing the damping of the system. The damping of the system can be adjusted by controlling the displacement of the variable displacement hydraulic motor or the payload of the generator.

By comparing the hydraulic motor displacement and the generator damping, a comparative simulation is conducted to obtain the relationship between the motor displacement and the power generation and the relationship between generator damping and power generation, as shown in Figs. 13 and 14,.

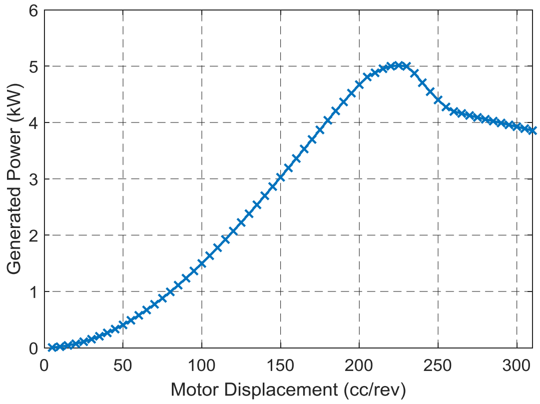

Fig. 13 Generated power vs Motor Displacement

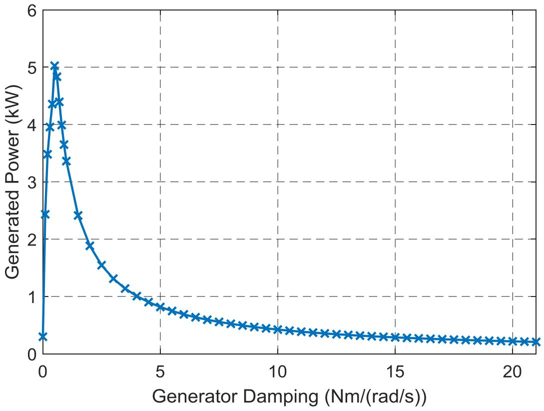

Fig. 14 Generated power vs Generator Damping

It's show that by adjusting the displacement of the hydraulic motor, there is an optimal damping position for the power generated by the PTO, when the motor displacement is 225cc/rev, the maximum generated power is 5.017kW. By adjusting the generator damping, there is also an optimal damping position for PTO generated power, when the generator damping is 0.5 Nm/(rad/s), The maximum generated power is 5.025 kW. From Fig.13 that if the motor displacement is individually adjusted, the motor displacement should be adjusted to be higher than 150 cc/rev to ensure that the generated power is greater than 3 kW. From Fig. 14, if the generator damping alone is adjusted, the damping must be adjusted within the range of 0.2-1 Nm/(rad/s).

In addition, by the lock/clutch control strategy of the buoy, the buoy can be locked at the crest/wave trough, that is, when the buoy speed is 0, and the buoy is released at an appropriate time to increase the power[10.11].

VII. CONCLUSION

The design and simulation of an oscillating buoy wave hydraulic PTO device is introduced. Based on the design of the oscillating buoy wave energy conversion device, the PTO system is analysed in frequency domain, the hydrodynamic characteristics of the model was analysed, and the transfer function of the linear PTO system was obtained. Under different damping conditions, the linear PTO system was obtained and the optimal damping theory was obtained by comparing the designed linear PTO damping conditions. Then, the hydraulic PTO system was designed and the simulation analysis of the hydraulic system was carried out. Finally, the system's motion restraint control was added and the damping comparison analysis simulation was performed. The relationship between hydraulic motor displacement, generator damping and generated power was obtained by adjusting the motor displacement and generator damping, so as to obtain the optimal damping position for different adjustment schemes. The designed wave energy conversion device not only improves the utilization efficiency of ocean energy, but also provides an effective control strategy for WEC in the marine complex environment and improves the extraction power efficiency.

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