Modelling and testing of hydraulic power take-off for wave energy converter on artificial breakwater

Jianan Xu, Tao Xu, and Yansong Yang

Abstract— **The development of new energy has become a historical trend and an inevitable choice in today's world, facing the problem that the possible greenhouse gas emissions and the decline of traditional fossil reserves including oil and coal. Marine energy is a renewable energy source that is green, clean and has huge reserves. The oscillating wave energy converter can effectively convert wave energy into power resources for human society. In this paper, an oscillating wave energy-converting device based on artificial breakwater is designed. Wave energy is captured by a buoy floating on the water, and then electricity generated with rotating generator driven by hydraulic power take-off (PTO) system. Design of the overall wave energy converter device is introduced in this paper. In addition, hydrodynamic parameters of the buoy are analysed by ANSYS/AQWA software including additional mass, damping coefficient and RAO. After that, the parameters of linear PTO are analysed with MATLAB/Simulink software. The hydraulic PTO system is designed and its electromechanical system is simulated with AMESim software. In addition, the damping is optimized with the simulation results of linear PTO and hydraulic PTO. The motion limitation of the buoy is accomplished by introducing the damping in PTO system. Finally, the feasibility of the designed hydraulic PTO system is examined by setting up a test bench.**

Keywords—**Artificial breakwater, Wave energy converter, Hydraulic power take-off, Optimal damping; Constrained motion.**

I. Introduction

WITH the rapid development of human society, the growing demand for energy has put forward higher requirements. Since the Industrial Revolution, petroleum, natural gas, coal and other fossil energy have been widely used. However, due to their limited reserves and non-renewable, the speed of fossil energy production has been far lower than the speed of human consumption of fossil energy. Fossil energy on the Earth is rapidly decreasing, which further causes the global energy crisis. At the same time, the exploitation and use of fossil energy will directly or indirectly damage the ecological environment and hinder the sustainable development of human beings. Therefore, for the sustainable development of mankind, it is of great importance to adjust the energy structure and develop and utilize renewable and clean energy.

The total area of the ocean is 361 million square kilometres, accounting for 71 % of the surface area on the earth. It is rich in marine energy resources, large in capacity and widely distributed, and is a green energy source. In fact, about 97 % of the water on the earth is seawater, and most of the heat that the sun illuminates the earth is absorbed by the seawater, so the ocean can be called the largest solar collector. As one of the important forms of ocean energy, wave energy is more and more concerned because of its high energy density and relatively small-time limit. It can realize the advantages of power generation and power supply with smaller devices [1-2].

In order to convert wave energy into electricity, a wave energy conversion device (WEC) must have a power take-off device (PTO) [3]. The PTO system should be able to work properly under tough marine conditions, so the hydraulic PTO system can be selected. There are many forms of WEC, mainly in the form of absorption, pressure difference, attenuation, termination, and oscillating water column. The types of PTO mainly include: turbine type, linear generator type, hydraulic unit type and so on.

An oscillating buoy wave energy hydraulic PTO device applied to the breakwater is mainly designed in this paper. The oscillating buoy wave energy device is small in size, high in energy density, and can be used together with other wind energy, tidal energy and solar power generation technologies. It can effectively convert ocean wave energy into electrical energy and improve resource utilization.

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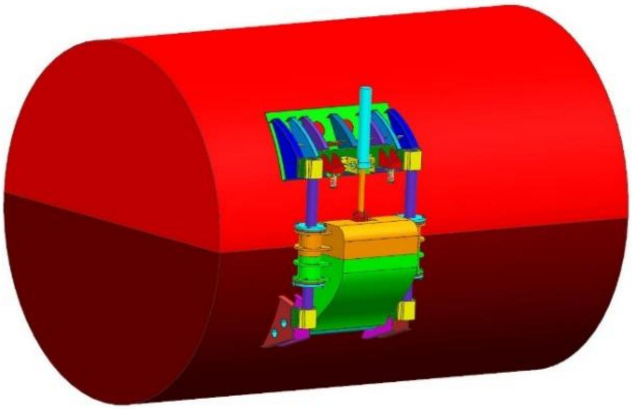

Fig. 1. The wave energy converter model on artificial breakwater.

II. MATHEMATICAL FORMULAE

The wave energy conversion device based on the breakwater is shown in Fig. 1. It is designed such that the WEC is placed on the breakwater floating on the surface of the water, and the movement energy of the wave transmitted to the buoy which is converted into electric energy by the hydraulic system connected.

The wave energy conversion device mainly includes the following three parts:

1) The main mechanical structure is mainly used to fix the wave energy replacing device on the breakwater.
2) The buoy structure is mainly used to acquire wave energy to generate reciprocating motion.
3) Hydraulic cylinder is mainly used to connect hydraulic PTO systems.

In addition, mechanical limit devices have been added to protect the safety of the device.

III. FREQUENCY DOMAIN ANALYSIS FOR WEC

The first step in designing WEC is frequency domain analysis. The modelling in frequency domain is essentially linear and does not take into account many non-linear characteristics that become prominent under extreme ocean conditions. Of course, it is necessary to fully consider when conducting in-depth analysis, but it is undeniable that frequency domain analysis helps to have a clear understanding of the preliminary design of WEC and the energy conversion performance of the device.

The linear wave theory makes the following assumptions:

Waves are two dimensional. The fluid is incompressible. There are no viscous losses. There is no underlying current. Small amplitude body motions. Wave height is much smaller than water depth or wave length.

The following, as derived by Jeffreys and Falnes [4,5], describes how to model the hydrodynamic forces on a WEC using linear wave theory in the frequency and time domain. If the mechanical mechanism is not restricted, it will have six degrees of freedom; three translational: heave, surge and sway; and three rotations: pitch, roll and yaw [6]. However, for the sake of simplicity, consider only a single degree of freedom with the body oscillating in the heave (vertical to the sea surface x, x = 0 in the steady state in the absence of waves), because this is the only direction of motion that can be used by the PTO to generate power. 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 and mooring. 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 can be linearized to obtain the linearized hydrostatic force.

$$f_{hs}(t) = -\rho g S x \tag{3}$$

Where ρ is the density of water,1.03 g/cm^3, g is the gravitational acceleration 9.8 m/s^2, S is the cross-sectional area of the buoy in the direction of motion, that is, the cross-sectional area of the buoy in contact with the surface of the water 2.4 m^2.

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

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

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 [7].

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

Where H is the wave height, 2 m. $\Gamma(\omega)$ is the positive real force coefficient 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 waves and the shape and quality of the buoy. ω is the frequency of the waves. The design of this system is based on the analysis of the regular wave period of 8 s, so $\omega = 0.125$ Hz.

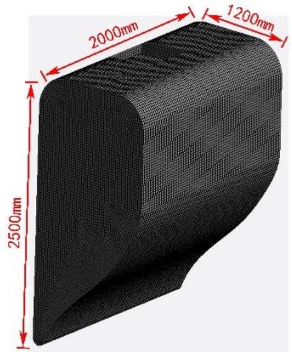

Fig. 2. The buoy shape and model mesh breakwater

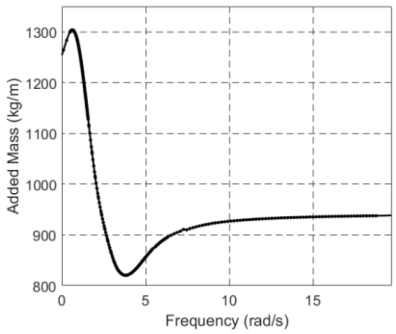

Fig. 3. The added mass of the buoy

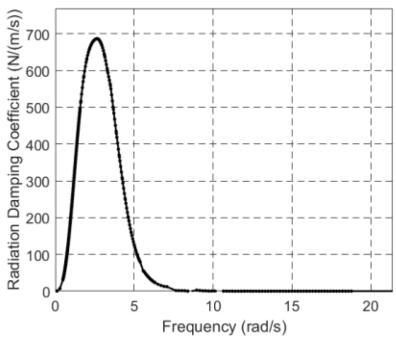

Fig. 4. The radiation damping coefficient of the buoy

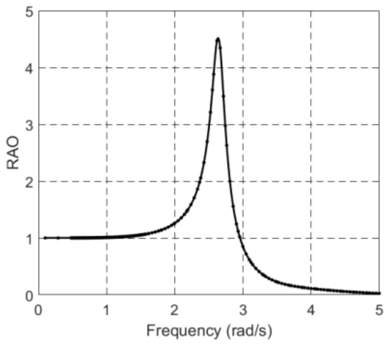

Fig. 5. The buoy shape and model mesh breakwater

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

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

Where the radiation force is

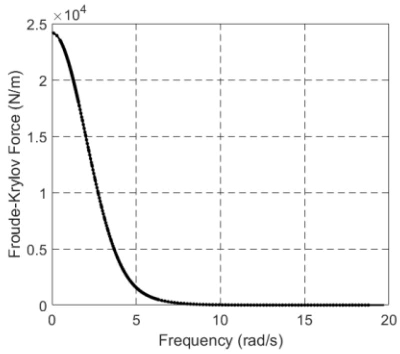

Fig. 6. The Froude-Krylov Force of the buoy

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

Displacement is

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

The radiation force can be decomposed in phase with the acceleration and velocity of the buoy [8]. 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 which 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 amplitude of the regular wave floater.

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

The ANSYS-AQWA software is used to calculate and analyse the additional mass $A(\omega)$ and the radiation damping coefficient $B(\omega)$ of the designed buoy shape. The buoy shape and the model mesh are shown in Fig. 2 below. The number of nodes is 31246 and the number of elements is 31244. According to the centre of gravity, moment of inertia, quality parameters calculated by UG software for hydrodynamic solution analysis, the additional mass A(ω) of buoy shown in Fig. 3, radiation damping coefficient B(ω) shown in Fig. 4. The design of the buoy additional mass is 1298 kg obtained in the 8s period wave, and radiation damping is 0.12 kNs/m.

IV. MODELLING AND SIMULATION OF LINEAR PTO

The mechanical force on the PTO mainly includes the PTO force and the mooring force. Assuming the mooring force is 0 and the PTO is a linear PTO, the mechanical force has the following expression:

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

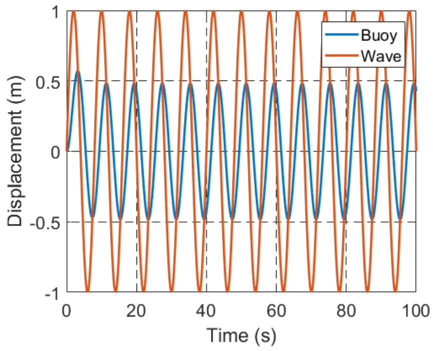

Fig. 7. Wave and WEC displacement

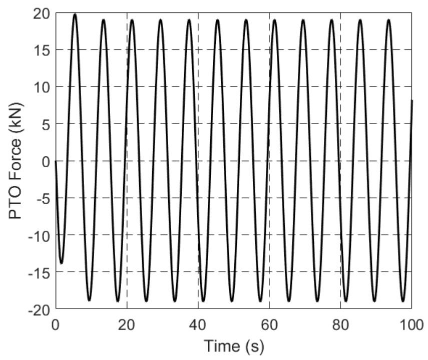

Fig. 8. PTO force

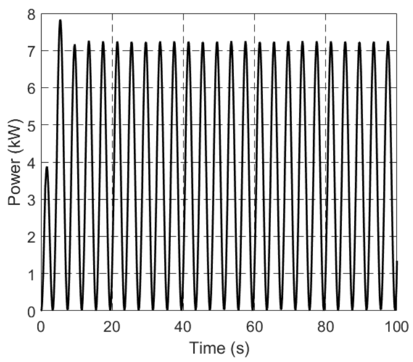

Fig. 9. The Froude-Krylov force of the buoy

Where K is the spring stiffness and C is the damping coefficient. Therefore, the formula of the linear PTO system can be obtained. [9]

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

Taking the Laplace transform gives

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

Convert the above equation to the frequency domain, get

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

The velocity is

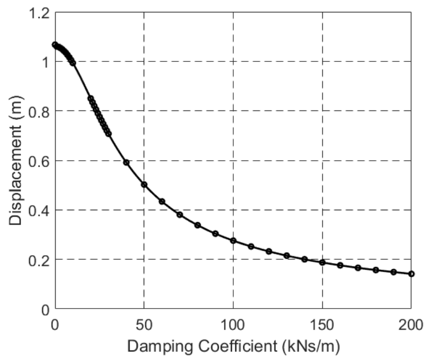

Fig. 10. WEC displacement in different damping coefficient

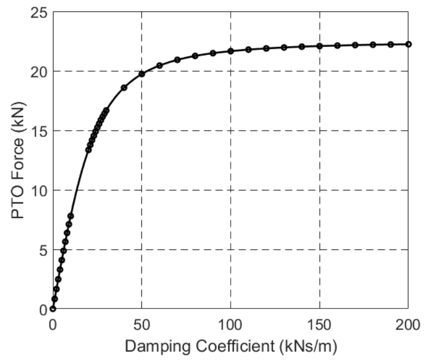

Fig. 11. PTO force in different damping coefficient

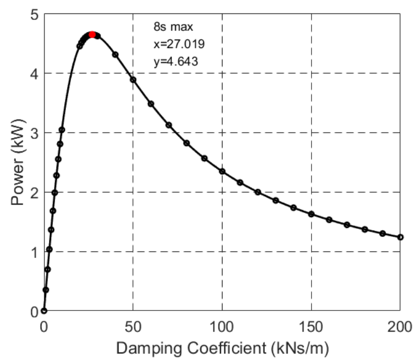

Fig. 12. Power in different damping coefficient

$$U(j\omega)=\frac{F_e(j\omega)}{(m+A)j\omega+B+C+\left(\frac{\rho g S+K}{j\omega}\right)} \quad (17)$$

Using MATLAB/Simulink software simulation to obtain the simulated data of the designed linear PTO in the regular wave height H = 2 m and period T = 8 s, and selecting the damping coefficient C = 50 kNs/m and spring coefficient K = 0 to simulate, the results shown in Figs. 7-9.

Fig. 12 shows that for a linear PTO, there is an optimal system damping that maximizes the linear PTO power, that is, when the damping C = 27 kNs/m, the maximum power generation is 4.64 kW.

Fig. 10 shows that if the displacement of the WEC is limited within ±0.5 m and the minimum power is kept above 3 kW, the damping C must be controlled between 50 and 70 kNs/m, which can not only guarantee the safe displacement of the WEC but also effectively increase the power.

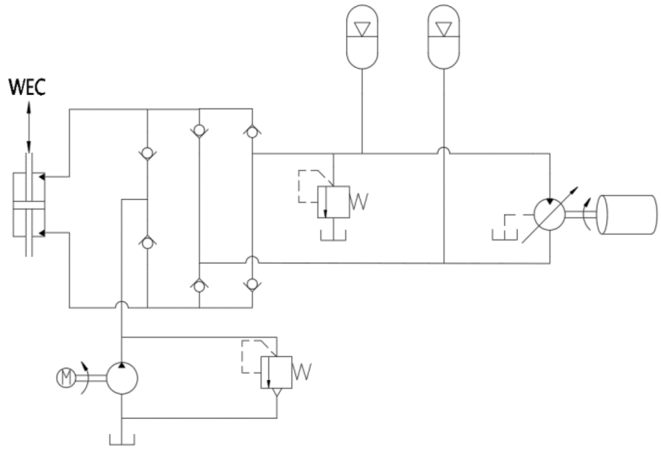

Fig. 13. Hydraulic PTO unit circuit diagram

The linear PTO system modelling and simulation can be obtained, PTO system has the best damping situation, by adjusting the appropriate damping can achieve both increase power and ensure the safety of the device displacement.

V. MODELLING AND SIMULATION FOR HYDRAULIC PTO

The hydraulic PTO for WEC has the advantage of being able to handle low-frequency high-force waves, and the power generation elements can be determined based on the power required, which is smaller, cheaper, and less efficient [10].

The linear PTO system modelling shows that the purpose of increasing power and reducing the WEC displacement can be achieved by adjusting the system damping, so in the hydraulic PTO, optimal situation can be obtained by adjusting the damping of the hydraulic system.

The hydraulic PTO system designed in this paper is modelled and simulated by AMESim software. The hydraulic circuit mainly includes: a hydraulic cylinder part for connecting the buoy and hydraulic PTO; a rectifying circuit makes the hydraulic oil always pass through the hydraulic motor in the same direction, so that the direction of oil input or output of the hydraulic motor will not be affected by the changes in the direction of motion of the hydraulic cylinder; the high and low accumulator parts are used to provide a stable pressure difference and stabilize the loop pressure to ensure the stability of the output; the charge oil booster device is used to ensure the minimum hydraulic pressure in the oil road which prevents the hydraulic pressure from being reduced due to leakage, etc. The hydraulic motor is used to connect the generator for power conversion. The entire hydraulic system is simple to construct, without complex components, and has good dynamic response characteristics. The hydraulic PTO unit circuit is shown in Fig. 13. The inner diameter of the hydraulic cylinder is 100 mm, and the diameter of the piston rod is 70 mm. In order to obtain uniform power generation, a double-acting double-rod hydraulic cylinder is used.

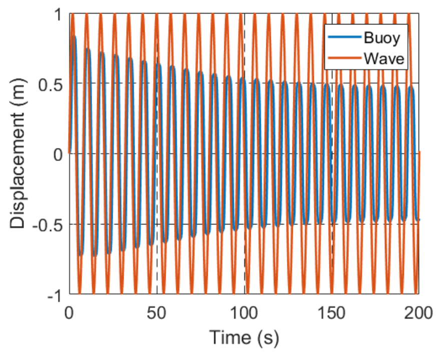

Fig. 14. WEC displacement

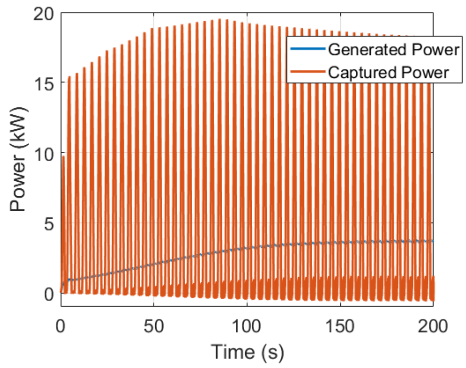

Fig. 15. PTO captured and generated power

In the entire PTO system, the safety valve, which is a protective device, is added and set to 350 bar to prevent dangerous pressure in 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 10 bar, 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 pressure of the piston chamber on both sides of the hydraulic cylinder, A_p is the area of the piston, is 0.024 m² and f_{PTO} is the PTO force in the hydraulic circuit, which value corresponds to the above f_m.

The captured power of the PTO system is

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

The generated power of the PTO system is

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

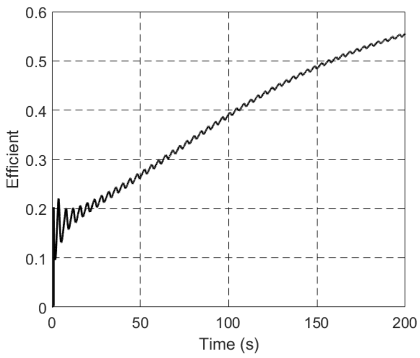

Fig. 16. PTO efficiency

Where ω_m is the output 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 respectively 30 and 10 bar, and D_m is hydraulic motor displacement, is 150 cc/rev. In addition, the one-way valve opening pressure is 0.2 bar and the maximum flow rate is 200 L/min.

In the hydraulic system simulation, the linear wave model established in the previous section is introduced, and the PTO force in the linear system model is changed to the hydraulic cylinder force corresponding to the dynamic hydraulic PTO, and the simultaneous solution is performed by AMESim software. The results analysed under the regular wave height H = 2 m and period T = 8 s are shown in Figs. 14-16.

It can be obtained from the simulation that the hydraulic PTO efficiency tends to 0.6, mainly due to the friction and loss factors added in the simulation, including the friction of the hydraulic cylinder is 1 kNs/m, the Coulomb friction is 2.1 kN, and the diameter of the pipeline used is 20 mm. The wall thickness is 2.75 mm and the total length is about 10 m. When the system is stable, the PTO capture power is 3.8 kW, the WEC displacement is kept within 1 m, that is, within ±0.5 m, and the hydraulic system meets the design requirements.

VI. CONSTRAINED MOTION CONTROL STRATEGY

As the wave energy conversion device operates in the sea, its operation will be affected by extreme weather. In order to ensure that the WEC can work normally and not be damaged in a harsh environment, a motion constraint control strategy is added. On the one hand, the hydraulic cylinder of hydraulic PTO works within a certain stroke. On the other hand, it will be ensured that the entire system will not be damaged in harsh environments.

The motion constraint control strategy mainly includes mechanical structural constraints and PTO system control strategy constraints.

On the one hand, by adding a limit device, the operation of the hydraulic system is prevented from being broken by the over-stroke operation of the buoy. On the other hand, by comparing the modelling and simulation studies of the linear PTO system above with respect to Figs. 10, 11, and 12, it is known that the maximum power can be obtained by changing the damping of the system, and the displacement of the WEC can be limited.

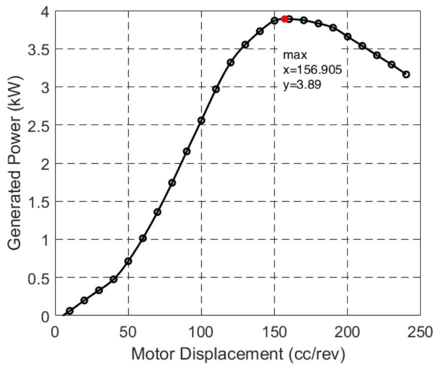

Fig. 17. Generated power vs motor displacement

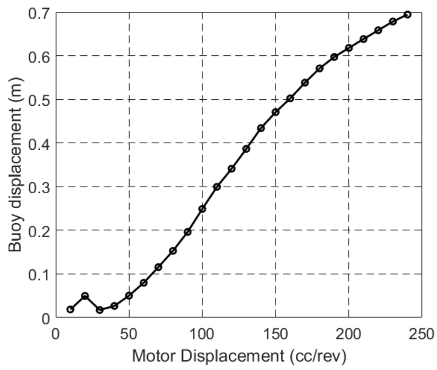

Fig. 18. Buoy displacement vs motor displacement

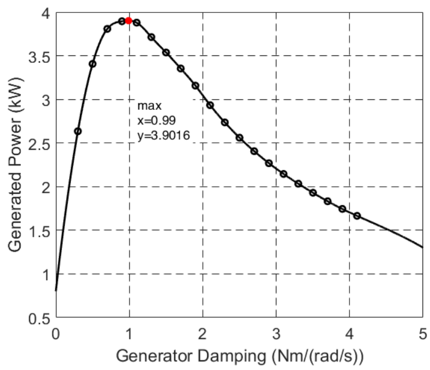

Fig. 19. Generated power vs generator damping

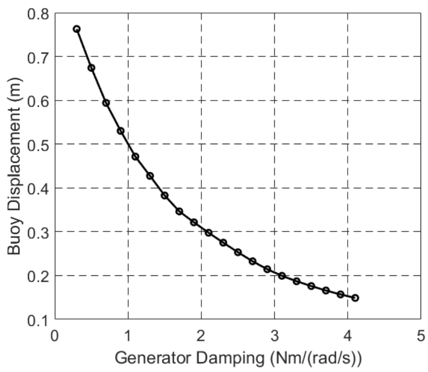

Fig. 20. Buoy displacement vs generator damping

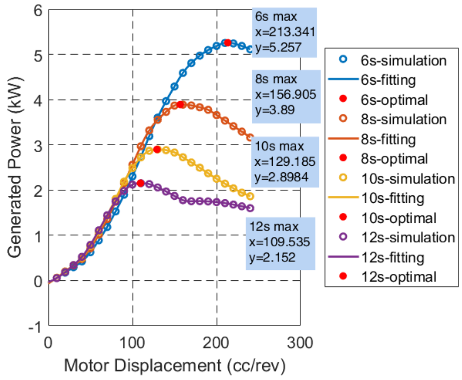

Fig. 21. Generated power vs motor displacement under 6-12 s wave period

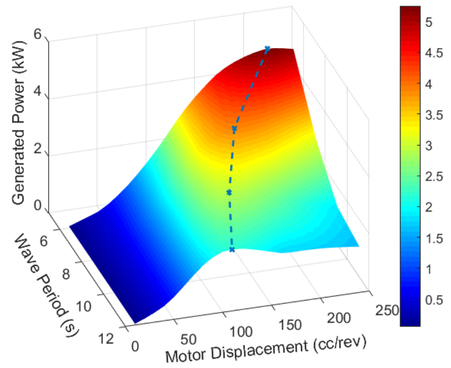

Fig. 23. Generated power vs motor displacement under 3-D Graphic

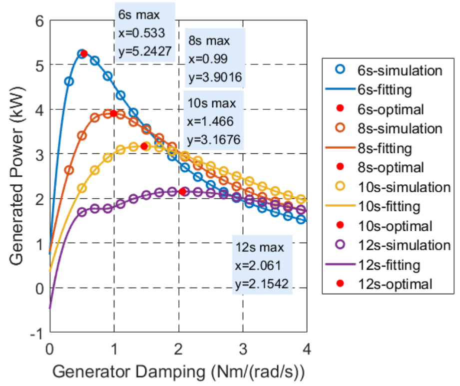

Fig. 22. Generated power vs generator damping under 6-12 s wave period

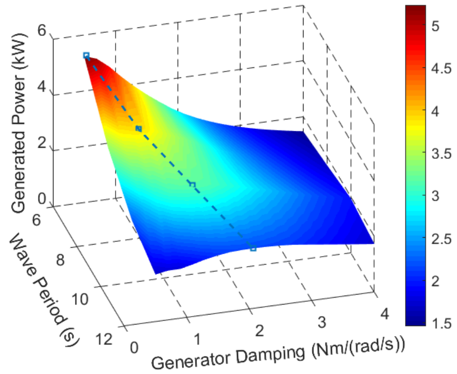

Fig. 24. Generated power vs motor displacement under 3-D Graphic

After several simulations, there are several ways to change the damping of the hydraulic PTO system:

1) Adjusting the displacement of the hydraulic motor.
2) Adjusting the parameters of the hydraulic cylinder, including the piston area, stroke, etc.
3) Adjusting the damping parameters of the generator.

This time, by tuning the displacement of the hydraulic motor and the motor damping, the simulation is carried out separately. In order to obtain the influence of different motor displacement and motor damping on the power generation situation, the fixed parameters are first set to prevent the hydraulic PTO system from losing speed due to the PTO damping being too small. So, the motor damping is 2.5 Nm/(rad/s) when changing the displacement of the hydraulic motor, and the hydraulic motor displacement is set to 100cc/rev when changing the motor damping. The relationship between the motor displacement and the power generation as shown in Fig. 17. And the relationship between the motor damping and the power generation is obtained in Fig. 19. It is depicted in Fig. 18 that the relationship between motor displacement and the buoy displacement. And the relationship between generator damping and the buoy displacement is shown in Fig. 20.

So, we could conclude that the buoy displacement is decreasing with the reduction in displacement of hydraulic motor. And the buoy displacement will rise while the decreasing in generator damping.

According to the simulation, by adjusting the hydraulic motor displacement, the PTO generated power has the best damping position, that is, when the motor displacement is 156 cc/rev, the maximum generating power is 3.89 kW; by adjusting the motor damping, the PTO generating power is optimal. The damping position, that is, when the motor damping is 0.99 Nm/(rad/s), has a maximum generating power of 3.9 kW. It can be seen from Fig. 17 that if the displacement of the motor is separately adjusted, the displacement of the motor should be adjusted within 110-250 cc/rev to ensure that the generated power is greater than 3 kW. It can be seen from Fig. 18 that if the motor damping is adjusted separately, the damping should be adjusted within the range of 0.5-2 Nm/(rad/s).

Besides, in order to ensure the buoy moves in a limited, the motor displacement and generator damping need to adjust within a certain range. From the Fig. 17-20, we can draw a conclusion that the buoy will less than ±0.5 m while keep the motor displacement within 160 cc/rev and keep the generator damping above 1 Nm/(rad/s).

At the same wave height, the power generation of hydraulic PTO in different wave periods, different displacements of hydraulic motors and different dampers of motors is obtained by comparing and simulating groups by changing wave periods, as shown in Figs. 21 and 22.

From Figs. 21-24, it can be seen that the larger the displacement of hydraulic motor, the smaller the system damping. The optimal damping decreases with the decrease of wave period, and the optimal generating power increases with the decrease of wave period. That is

Fig. 25. Hydraulic PTO test bench

to say, the optimal damp of the system is closely related to the wave period. By adjusting the damp of the system, the optimal power generation can be obtained under various sea conditions. Furthermore, the most effective method to optimize the damping of hydraulic PTO in this paper are tuning the displacement of hydraulic motor and the damping of generator.

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 [11-15].

VII. CONSTRUCTION OF EXPERIMENTAL PLATFORM

In order to verify the feasibility of the PTO system, the test equipment is built up. The structure of test bench is shown in Fig. 25, which is composed of four parts: electric cylinder, hydraulic circuit, power generation system and electric controlling system.

Among them, the main role of the electric cylinder is to simulate the wave motion with single degree of freedom. Hydraulic cylinder, rectifier circuit, hydraulic motor and pump station system is included in hydraulic circuit, which is same as the hydraulic circuit in simulation. Permanent magnet synchronous generator and rectification circuit constitute the power generation system. The electronic controlling system mainly includes the control system of the electric cylinder and the variable hydraulic motor, and the data acquisition of the sensor including the pressure transducer and torque speed sensor.

VIII. CONCLUSION

The design, simulation and test of an oscillating buoy wave energy hydraulic PTO device based on artificial breakwater is mainly introduced in this paper. The design of the oscillating buoy wave energy conversion device is introduced. Then the frequency domain analysis of the PTO system is carried out by ANSYS-AQWA software. The hydrodynamic characteristics of the model are analysed, and the transfer function of the linear PTO system is obtained. Then the linear PTO model is established and passed. The simulation analysis of MATLAB software shows the linear PTO system under different damping conditions and compares the designed linear PTO damping to obtain the optimal damping theory. After that, the hydraulic PTO system was designed, and the hydraulic system was simulated and analysed by AMESim software. The hydraulic PTO analysis and calculation under the action of linear wave was completed by introducing linear wave theory. Finally, the motion constraint control of the system is added and the damping contrast analysis and simulation are carried out. The relationship between the hydraulic motor displacement, the motor damping and the generated power is obtained by adjusting the motor displacement and the motor damping, thereby further completing the optimal damping of the system under different wave period. The wave energy conversion device designed in this paper not only improves the utilization efficiency of marine energy, but also provides an effective control strategy for WEC working in a complex marine environment and improves the extraction power efficiency. And the test bench has been built up and lay a solid foundation for the further work.

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