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ESTABLISHMENT OF MOTION MODEL FOR WAVE CAPTURE BUOY AND RESEARCH ON HYDRODYNAMIC PERFORMANCE OF FLOATING-TYPE WAVE ENERGY CONVERTER

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ABSTRACT

Floating-type wave energy converter has the advantages of high wave energy conversion efficiency, strong shock resistance ability in rough sea and stable output power. So it is regarded as a promising energy utilization facility. The research on hydrodynamic performance of wave capture buoys is the precondition and key to the wave energy device design and optimization. A simplified motion model of the buoys in the waves is established. Based on linear wave theory, the equations of motion of buoys are derived according to Newton's second law. The factors of wave and buoys structural parameters on wave energy absorption efficiency are discussed in the China's Bohai Sea with short wave period and small wave height. The results show that the main factor which affects the dynamic responses of wave capture buoys is the proximity of the natural frequency of buoys to the wave period. And the incoming wave power takes a backseat role to it at constant wave height. The buoys structural parameters such as length, radius and immersed depth, influence the wave energy absorption efficiency, which play significant factors in device design. The effectiveness of this model is validated by the sea tests with small-sized wave energy devices. The establishment methods of motion model and analysis results are expected to be helpful for designing and manufacturing of floating-type wave energy converter.

Keywords: wave energy, linear wave, floating-type, hydrodynamic, absorption efficiency

INTRODUCTION

With the development of the economy and society, all the countries face increasing energy demand that lead to rapidly growing greenhouse gas emissions and increased pollution, a large portion of which come from conventional energy production and usage. People now turn their attention to renewable energy resources. Sea wave energy is being increasingly regarded as a major and promising resource [7,1,2] in many countries for its advantages of substantial deposits and high energy quality. Wave energy development and utilization are generally achieved by wave energy converters (WECs). High-efficiency WECs can greatly improve the utilizing ratio of wave energy [11]. Various types of WECs, such as oscillating water column (OWC), oscillating buoy, contraction channel, floating and duck type, have been developed by some colleges and research organizations in the world [5]. Among them, floating-type wave energy converter generally has the advantages of high wave energy conversion efficiency, strong shock resistance ability in rough sea and stable output power [9,16]. So it is regarded as a promising future energy utilization way. "Pelamis" are the most famous WECs in operation that developed by the Scottish company Pelamis Wave Power (PWP) in UK. The Pelamis P2 has five sections linked by four joints. The sections have a diameter of 4m and a length of 36m. The overall machine length is 180m. It is currently rated at 750 kW depending on the conditions at the chosen wave farm site [14].

In this paper, a multi-section floating-type wave energy converter is chosen as study object (Fig.1). The device is composed of multi-section cylindrical buoys which are hinged together. Their function is to gather wave energy by converting wave kinetic and potential energy of the irregular reciprocating motion to kinetic energy of wave capture buoys in term of resonance in the waves. Power take-off (PTO) system adopts hydraulic energy conversion system that is installed between two adjacent hinged buoys. Its function is to extract kinetic energy of wave capture buoys and provide input energy of the electric generator. The device is arranged along wave direction and partially submerged in seawater. The basic working process is as follow: (1) the angle between adjacent hinged buoys ongoing changes with buoys mechanical motion in wave; (2) hydraulic cylinder pistons are driven to do reciprocating motion; (3) the high pressure oil that produced from hydraulic cylinders drives the hydraulic motor and then turns the generator that connected to it to produce electricity.

Fig. 1. Schematic diagram of the floating-type wave energy converter (1-1~1-4: wave capture buoys; 1-5~1-7: hydraulic energy conversion systems; 1-8: mooring system)

The design of wave capture buoys has important effects on wave energy conversion efficiency and adaptive capacity in rough sea conditions, which ultimately affect the key indicators of the WECs such as generating efficiency, quality of power supply and viability. This paper established a simplified buoys motion model based on linear wave theory, and then discussed the factors of wave parameters and buoys structural parameters on wave energy absorption efficiency.

MATHEMATICAL MOTION MODEL OF BUOYS

To simplify the problem, the buoys of the floating-type wave energy converter are comprised of two cylindrical pontoons of equal length and equal diameter that are hinged together by a hydraulic energy conversion device and partially submerged in the seawater with weight evenly distributed. The device is arranged in the seawater of appropriate depth. The analysis is based on simplified cases where wave is treated as linear, regular waves with an incidence angle of 0.

KINEMATIC DECOMPOSITION OF THE BUOYS MOTION

For the dynamic analyses of the device, we can set a single buoy as the object of study. In the rectangular coordinate system (x, y, z) as shown in Fig.2, the buoys motion can be disassembled into two independent motions: heaving motion along the z-axis and pitching motion around the centre point O of the adjacent buoys. The pitching angle of buoys is small because the retractable length of hydraulic cylinder piston is minute compared with the buoys radius and length in the sea conditions of short wave period and small wave height. The movements of buoys can be thought of as heaving motion approximately.

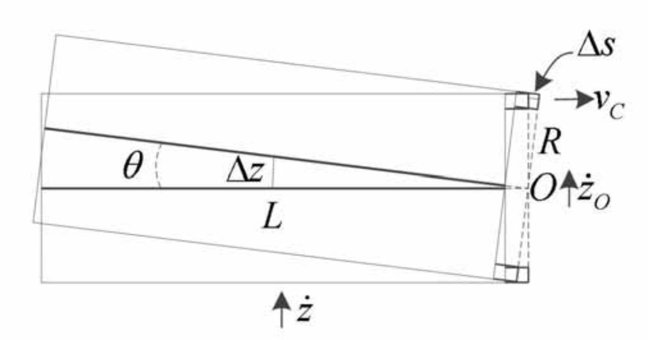

Fig. 2. Schematic diagram of buoy motion decomposition

We assume that the displacement of buoys heaving motion is z and the speed is $\dot{z}$, the speed of centre point along the z-axis is $\dot{z}_O$. The displacement and speed of the two hydraulic cylinder pistons are approximately equal respectively. The pitching angle θ around the centre point is little.

$$\Delta z = (\dot{z} - \dot{z}_O)\Delta t \approx (L/2)\cdot \sin\theta \,,\ \Delta s = v_C \Delta t \approx R\sin\theta \tag{1}$$

Where Δz is the motion displacement of buoys gravity center in the time of Δt, Δs is the motion displacement of hydraulic cylinder pistons in the time of Δt.

$$(\dot{z} - \dot{z}_O)\cdot t/(L/2) \approx v_C \cdot t/R \tag{2}$$

Where v_C is the speed of hydraulic cylinder pistons, r is introduced as the proportionality coefficient of speed: $r = \dot{z}_O / \dot{z}$.

$$v_C \approx 2(1-r)R\dot{z}/L \tag{3}$$

EQUATIONS OF BUOYS MOTION

As shown in Fig.3, according to the force analysis of single buoy, the buoy mainly accepts gravity mg, buoyancy F_f, wave force F_V, hydrostatic restoring force F_S and hydraulic damping force f. Among them, gravity and buoyancy are equal and opposite. According to the analysis mentioned above, the motion of the buoys is simplified as heaving motion. Based on the principle of energy equivalence, an equivalent damping force F_C along z-axis is assumed that it can achieve the same working effect to buoys as that of the hydraulic damping force f. The buoys make simple harmonic vibration affected by these forces in vertical direction. The equivalent damping force F_C and wave force F_V are opposite in direction. The force analysis is made according to Newton's second law as following.

$$\left(m+m_W\right)\cdot\ddot{z}=F_V+F_C+F_S \tag{4}$$

Where m is the buoy mass, m_W is the added mass of buoy, $m_W=\pi\rho R^2 L/2$ [10] (horizontal cylinder), $\ddot{z}$ is the heaving motion accelerated speed.

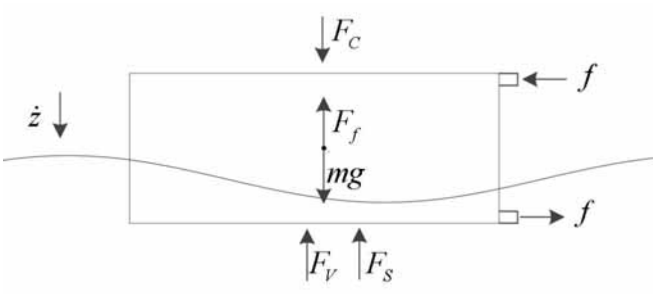

Fig. 3. Schematic diagram of buoy force analysis

The hydraulic cylinders adopt linear damping, based on the equivalent principle mentioned above, the following equation is derived.

$$\int F_C\cdot\left(\dot{z}-\dot{z}_O\right)dt=\int -2f\cdot v_C dt,\quad \text{so:}\quad F_C\cdot\left(\dot{z}-\dot{z}_O\right)=-2f\cdot v_C \tag{5}$$

by using the equation (3) and (5):

$$F_C=-2f\cdot v_C/\left(\dot{z}-\dot{z}_O\right)=-2C\cdot v_C{}^2/\left(1-r\right)\cdot\dot{z}=-8C\left(1-r\right)R^2\cdot\dot{z}/L^2 \tag{6}$$

Where C is damping coefficient, $f=Cv_C$.

Wave force of buoys in the linear wave can be represented as follow:

$$F_V=F_0\cos\omega t \tag{7}$$

Where F_0 is amplitude of wave force that can be solved by the methods of theoretical analysis or numerical simulation, ω is wave circular frequency.

The hydrostatic restoring force F_S of buoys in the waves can be calculated by the following formula [12]:

$$F_S=-\rho g A_{WP} z \tag{8}$$

Where ρ is the seawater density, A_{WP} is the wetted surface of buoy, $A_{WP}=2L\sqrt{2dR-d^2}$ (horizontal cylinder). d is the immersed depth of buoy.

Take formula (6), (7) and (8) into formula (4), the equations of motion of buoys are derived.

$$\left(m+m_W\right)\cdot\ddot{z}+8C\left(1-r\right)R^2\cdot\dot{z}/L^2+\rho g A_{WP} z=F_0\cos\omega t \tag{9}$$

WAVE ENERGY CONVERSION EFFICIENCY OF THE WECS

Wave energy conversion efficiency of WECs can be expressed as wave energy absorption efficiency [13]. This paper uses η_1 and η_2 to represent the wave energy absorption efficiency of buoys and hydraulic system respectively.

$$\eta_1=\overline{P}_F/P_{SEA},\ \eta_2=\overline{P}_C/P_{SEA} \tag{10}$$

Where $\overline{P}_F$ is the average wave energy absorption power of buoys, $\overline{P}_C$ is the average wave energy absorption power of hydraulic system, P_{SEA} is the input power of wave [6].

$$P_{SEA}=\rho g^2 H^2 T\cdot B/32\pi \tag{11}$$

Where B is the immersed width of buoys, H is wave height, T is wave period.

$$\overline{P}_F=\frac{1}{T}\int_0^T P_F dt=\frac{1}{T}\int_0^T F_V\cdot\dot{z}dt \tag{12}$$

Where P_F is the wave energy absorption power of buoys.

$$\overline{P}_C=\frac{1}{T}\int_0^T f v_C dt=\frac{1}{T}\int_0^T C v_C\cdot v_C dt=\frac{C}{T}\int_0^T\left[\frac{2\left(1-r\right)R\dot{z}}{L}\right]^2 dt \tag{13}$$

RESULT AND ANALYSIS

Wave energy absorption efficiency of the device is computed and analyzed using the above motion model of wave capture buoys. The wave parameters are from the China's Bohai Sea with short wave period and small wave height [15].

ANALYSIS ON INFLUENCE OF WAVE PARAMETERS ON WAVE ENERGY ABSORPTION EFFICIENCY

1. Variation of wave energy absorption efficiency with wave period

The effects of the wave period on the wave energy absorption efficiency of buoys and hydraulic system are analyzed in the case that the length of buoy is 8.0m, radius is 1.0m and the damping coefficient of hydraulic system is 5.0×10^{4}N·s/m, it's result shown in Fig.4.

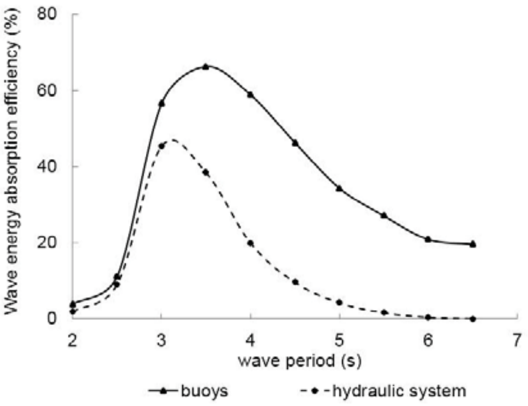

Fig. 4. Variation of wave energy absorption efficiency with wave period

Wave energy absorption efficiency of buoys and hydraulic system attain their maximum that are 65% and 45% respectively when the wave period is in the range of 3.0 s to 3.5 s. Outside this range, both of them quickly drop. The natural frequency of the buoys is also in the range. When the wave period is 2.5 s, their efficiencies can reduce to less than 10%. When the wave period exceeds 6.0 s, the wave energy absorption efficiency of hydraulic system is already close to 0 although the buoys' still remains at the levels of 20%. The calculation result verified that the main factor which affects the dynamic responses of wave capture buoys is the proximity of the natural frequency of buoys to the wave period [3, 4]. This is the primary factor for design of the WECs.

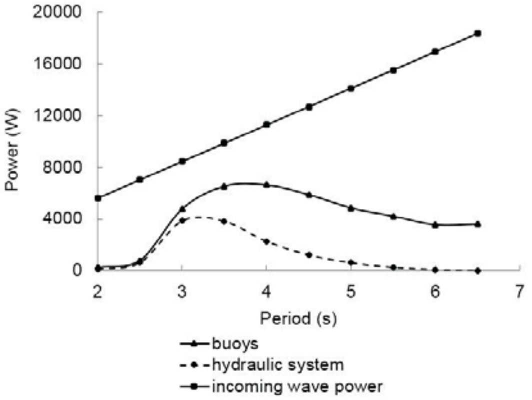

Fig. 5. Variation of absorbing power of device and incoming wave power with wave period

Fig.5 shows the variation of absorbing power of device and incoming wave power with wave period. We can see that the incoming wave power increases with wave period. Wave energy absorbing power of buoys and hydraulic system attain the maximum when the wave period is 3.7 s and 3.2 s respectively, and then start to decrease. Therefore, incoming wave power is a minor factor which affects the dynamic responses of wave capture buoys at constant wave height.

(2) Variation of wave energy absorption efficiency with wave height

Fig.6 shows the variation of absorbing power of device with wave height.

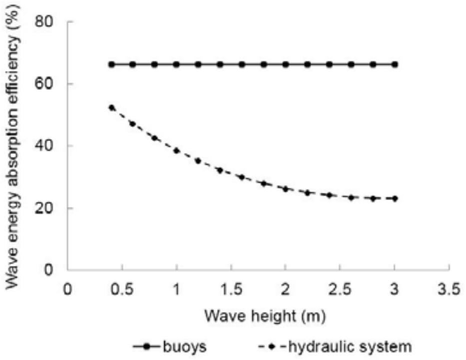

Fig. 6. Variation of wave energy absorption efficiency with wave height

For a floating-type WEC with permanent structures, no matter how the wave height changes, the wave energy absorption efficiency of buoys usually keeps unchanged, but the wave energy absorption efficiency of hydraulic system will decrease gradually. Therefore, smaller wave height can help to promote the wave energy absorption efficiency of hydraulic system. But enough force of hydraulic cylinder piston cannot be produced possibly that the system operating time reduces. This would finally cause insufficient of output power. Instead, if the wave height is too high, the force of hydraulic cylinder piston would exceed the allowable maximum working pressure that will cause the system to break. Therefore, an important consideration for hydraulic system design is the wave height in the site sea.

ANALYSIS ON INFLUENCE OF BUOYS STRUCTURAL PARAMETERS ON WAVE ENERGY ABSORPTION EFFICIENCY

The buoys structural parameters mainly include the length, radius and immersed depth. Next up are selecting the sea conditions that the wave height is 1.2 m and period is 3.5 s.

1. Variation of wave energy absorption efficiency with length of buoy

Fig.7 shows the variation of wave energy absorption efficiency with length of buoy. Both wave energy absorption efficiency of buoys and hydraulic system attain their maximum when the length is in the range of 7.0m to 8.0m. The main influence factors include the wave force, buoys mass, added mass and immersed area.

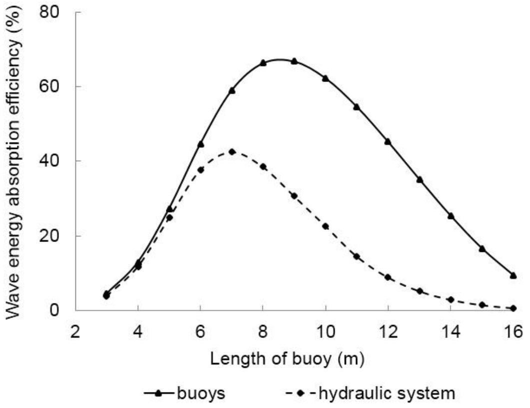

Fig. 7. Variation of wave energy absorption efficiency with length of buoy

2. Variation of wave energy absorption efficiency with radius of buoy

As shown in Fig. 8, both wave energy absorption efficiency of buoys and hydraulic system attain their maximum when its radius is about 1.8 m. Wave energy absorption efficiency of buoys tops out at 98% and resonance can be thought to occur.

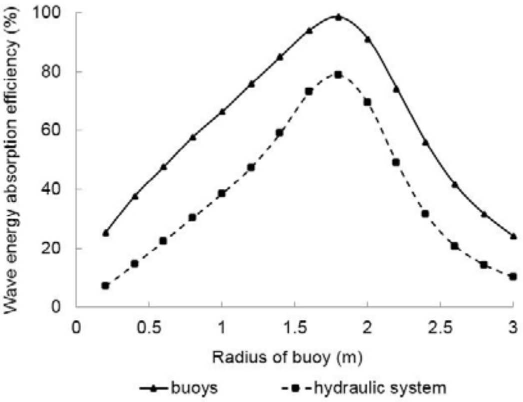

Fig. 8. Variation of wave energy absorption efficiency with radius of buoy

3. Variation of wave energy absorption efficiency with immersed depth of buoy

Fig.9 shows the variation of wave energy absorption efficiency with immersed depth of buoys when the length is about 8.0 m and the radius is 1.0 m. Both wave energy absorption efficiency of buoys and hydraulic system attain their maximum at the immersed depth of about 1.5 m, then starts to decline sharply. Their efficiencies fall below 10% with the immersed depth exceeding 1.8 m. The immersed depth depends on the buoys mass that changes the action area of wave force. Within certain realms of immersed depth of buoy, both wave force and mass inertia tend to continuously increase until the maximum number is attained. The main reason is that the growth rate of wave force exceeds the growth rate of mass inertia at the initial stages. After that, the immersed area of buoy decrease rapidly leading to reduce of wave force. And then the efficiency would be falling more quickly under the joint action of decrease of wave force and increase of mass inertia.

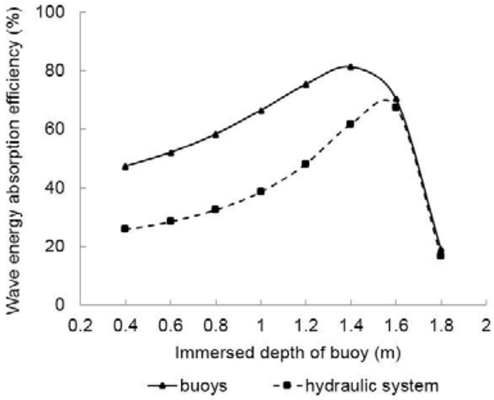

Fig. 9. Variation of wave energy absorption efficiency with immersed depth of buoy

MODEL VALIDATION

Research team of Professor Gao Hongtao, Dalian Maritime University in China, has carried out several sea tests with small-sized floating wave energy devices in Dalian sea area in 2012 and 2013. The wave capture buoys of testing apparatus are made up of several cylindrical buoys that can hinge together freely. The radius of power buoys is 0.5 m and the wave height is in the range of 0.4 m to 0.6 m. The device length is determined by changing the number of buoys combinations and the buoys immersed depth are adjusted by changing the self weight of device. Fig.10 is the generation power distribution diagram which the length is 4.0 m. The test results showed that the average output power is about 40W in the sea tests of 2013, and the maximum output power can achieve 100W when the instant wave height is about 1.0 m. In the sea tests of 2012, the average output power is about 20W that the test wave height measured is 0.5m when the length of buoy is 2.5 m. The energy conversion efficiency of the hydraulic system is about 15% in the on-land-experiment [8]. As shown in Fig.11 which are average generation output powers according to the model, the calculation values of the model basically agrees well with sea tests results. So we can get the conclusion that the model that we established in this paper is effective and available.

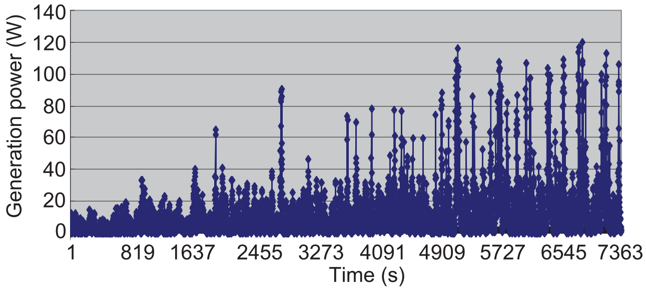

Fig. 10. Generation power distribution in 2013

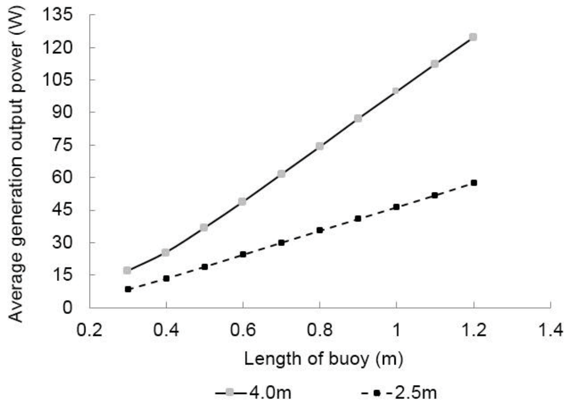

Fig. 11. Variation of average generation output power with wave height when the length of buoy is 4.0m and 2.5m

CONCLUSIONS

This paper takes the floating-type wave energy converter as research object. Based on linear wave theory, the equations of motion of buoys are derived according to Newton's second law and the factors of wave parameters and buoys structural parameters on wave energy absorption efficiency are discussed. The main conclusions are as follows:

1. For a floating-type wave energy converter whose structure size and hydraulic damping are determined, the main factor which affects the dynamic responses of wave capture buoys is the proximity of the natural frequency of buoys to the wave period. And the incoming wave power takes a backseat role to it at constant wave height.
2. Buoys structural parameters such as length, radius and immersed depth can impact the wave energy absorption capacity under the condition of the constant wave parameters. There is always a maximum in absorption efficiency.

The effectiveness of this model was validated by comparing this model calculation results with the sea test data from small-sized wave energy devices. The results showed that the two results are approximately identical.

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