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Applicability analysis of the wave energy converter in low wave energy density sea areas

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Abstract. The capture power of wave energy converter is affected by the interaction between the buoy and wave. This study aims to investigate the interaction between the buoy and wave motion in low wave energy density seas using the hydrodynamic calculation software AQWA and to achieve a reasonable optimal configuration for the greater capture power based on the orthogonal experiment. Results show that the wavelength in the resonance state increases with the increasing of buoy mass and increases first and then decreases with the increasing of buoy diameter. Taking capture power as the optimization goal, applicability analysis denotes that the wave energy converter with the mass of 4.2 t and the buoy diameter of 4 m is suitable for the Bohai Sea and the north of the Yellow Sea. The maximum capture power of 150 W is obtained in the Bohai Strait owing to the wavelength of 14 m. This study provides a new idea for the mass control, diameter selection and arrangement of the wave energy converter.

1. Introduction

Wave energy is considered as a clean energy resource with significant development potential, whose utilization is of great value to promote economic development. It is found that the conversion of wave energy is affected by many factors such as marine environment, geographical location and buoy structure. Sheng et al.[1] designed a kind of wave energy converters, realizing the energy conversion and utilization from the wave energy to hydraulic energy. However, the size of the wave energy converter was in the range of 12-36 m, which limited the application in the low wave energy density sea area. Bracco et al.[2] studied the effect of the buoy shape on wave energy conversion efficiency and hydrodynamic performance of the wave energy converter. It was found that the extracted power of the wave energy converter was increased by three times owing to the enhancement in the pitch and roll angle of the buoy by adding two wings. In addition to the buoy diameter, the effect of the mass on the capture power was investigated by Li et al.[3] Results indicated that the average output power was increased by 88.12 % with the decreasing mass. Wang and Mao.[4] studied the capture width ratio from the aspect of the wave period. Results demonstrated that the capture width ratio increased first and then decreased with the increasing wave period. However, there are few studies on the influence of the interaction effect between the buoy and wave on the capture power of wave energy converter, especially in the low wave energy density sea area.

In order to exploit the potential of the low wave energy density sea area and obtain the greater capture power, the interaction between the mass, diameter and the wavelength in the resonance state was evaluated using the frequency and time domain analysis. The results of this study can provide a reference for the design and application of the wave energy converters in the low wave energy density sea areas.

2. Mathematical model

2.1. Structure and function principle

The novel sealed buoy wave energy converter (SBWEC) was utilized to study the interaction between the mass, diameter and wavelength in the low wave energy density seas. As shown in Figure 1, SBWEC was mainly composed of buoy, slider, rotating arm, guide, gearbox and generator. It was distinct from the conventional point absorber wave energy converter[5]. Under the effect of wave motion, the energy conversion of wave energy to electrical energy was achieved relying on the rotation of the slider around the central axis of the buoy.
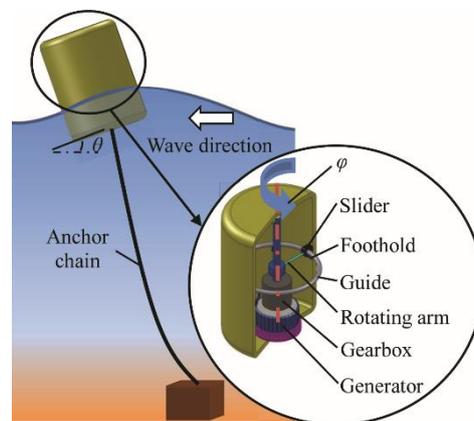

Figure 1. The structure of SBWEC

In Figure 1, an inclination angle θ between the buoy and the sea level was obtained by the wave motion. As a result, the internal slider was tilted θ synchronously with the buoy motion, so that the slider pushed the rotating arm to rotate φ around the central axis of buoy. Therefore, the gravitational potential energy was converted to the mechanical energy of the gear.

2.2. Structure and function principle

In order to simplify the analysis of wave and build a reasonable wave model, the wave was assumed to be ideal fluids of tack-free, incompressible and spin-free. Thus, the profile shape in the direction of propagation can be modeled as a sine function[6],

$$\xi(t,x) = \frac{H}{2}\cos(k_w x - \omega t) \tag{1}$$

Where H is the wave height. k_w is the wave number. $k_w = 2\pi/L$. L is the wavelength. ω is the wave angle frequency. Therefore, the equation of the slider motion in the vertical direction $Z(t)$ is represented as[7],

$$Z(t) = \frac{F_e(\omega,t)}{\sqrt{\left[k - (M + m_m(\omega) - m_{su})\omega^2\right]^2 + \left[(b_{hyd}(\omega) - b_{ext})\omega\right]^2}}\xi(t,x) \tag{2}$$

Where M, m_m and b_{hyd} are the SBWEC mass, the added mass coefficient and hydrodynamic damping coefficient, respectively. $k = \rho_{wg}AD$, where AD is the projected area of the underwater. b_{ext} is the external damping coefficient. F_e is the exciting wave force.

After the energy transfer through the buoy internal mechanism, the output power of the generator is represented as follows,

$$P_g = M_s g \eta \omega z(t) \tag{3}$$

Where M_s is the mass of slider. P_g is the output power of the generator, η is the transmission efficiency of the buoy internal mechanism, which is determined as 0.9[8,9].

2.3. Boundary paramerers

In this study, the wave climate of Shandong Peninsula was selected as low wave energy density seas to investigate the interaction between the SBWEC mass, diameter and wavelength. According to the past 10 years statistical analysis of the wave energy around the Shandong Peninsula[10-13], the wave parameters was summarized in Table 1. As for buoy, the diameters D of 2-5 m were selected. The height H_b and wall thickness b of buoy are 4 m and 0.03 m, respectively. The slider mass M_s and the SBWEC mass M are 20-50 Kg and $2.2-4.2 \times 10^3$ Kg, respectively. In addition, the simulation results were independent of the grid.

Table 1. The wave parameters of the Bohai and Yellow Sea

Parameter		Value			
		Spring	Summer	Autumn	Winter
The wave period of the Bohai T/s	Bohai Bay	2.8	2.8	2.5	2.6
	Central Bohai	2.7	2.7	3.0	3.5
	Bohai Strait	3.0	3.0	3.0	3.0
The wave period of the Yellow Sea T/s	North of the Yellow Sea	2.7~3.3	2.5~3.5	2.7~4.1	3.2~5.1
	Centra the Yellow Sea	2.0~3.2	3.0~3.9	2.8~3.7	2.0~4.8
	South of the Yellow Sea	3.0~4.1	2.0~4.5	3.0~4.8	3.8~7.0
Wind V_{wi}/m·s^{-1}	The average wind speed	6			
Current V_c/m·s^{-1}	The average current speed	0.1			
Water depth h/m	The average water depth	44			
Wave spectrum		*JONSWAP*			

3. Results and discussion

3.1. Interaction between the mass and wavelength in resonance state

As shown in Figure 2, the interaction between the mass and wavelength was studied in resonance state based on the pitch time domain response of the buoy. It is noted that the wavelength in the resonance state gradually increased with the increasing buoy mass. In Figure 2 (a), when D was 2 m, the minimum wavelength in the resonance state was 7.32 m at M 2.2 t and the maximum wavelength in the resonance state was 9.11 m at M 4.2 t. The wavelength required to achieve resonance was increased by 24.45 %. Similar to Figure 2 (a), the wavelength required to achieve resonance was increased by 25.32 % Figure 2 (b). Results found that a longer wavelength was required to achieve resonance with the increase in the wave energy converter mass, generating higher capture energy.

In Figure 2 (c) and (d), it was also shown that the wavelength in the resonance state gradually increased with the increasing buoy mass. When D was 4 m, the minimum wavelength in the resonance state was 6.41 m at M 2.2 t and the maximum wavelength in the resonance state was 13.97 m at M 4.2 t. The wavelength required to achieve resonance was increased by 117.94 % with the increase in the buoy mass from 2.2 t to 4.2 t. For the buoy with D 5 m, the wavelength required to achieve resonance was increased by 29.56 %. It was indicated that the wavelength in the resonance state was most sensitive to the variation in the buoy mass when D was 4 m.
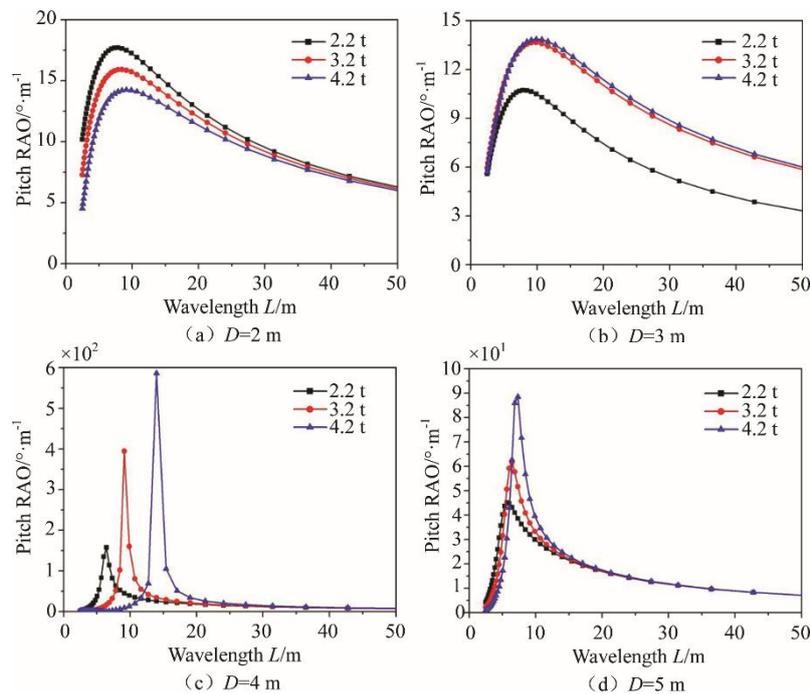
Figure 2. Relationship between the buoy mass and wavelength in the resonance state

3.2. Interaction between the diameter and wavelength in resonance state

Figure 3 displays the interaction between the buoy diameter and wavelength in resonance state. It was found that the maximum pitch RAO of the buoy was almost equal at the diameter 2 m and 3 m except for the case in Figure 3 (a). From a global perspective, the pitch RAO of the buoy increased with the increasing buoy diameter and reached the maximum value at the buoy diameter 4 m then decreased again. This meant that the buoy diameter 4 m was the optimal parameters to reach resonance with the waves when the buoy in the diameter ranges of 2-5 m. It was indicated that the buoy with the diameter 4 m formed a strong low frequency resonance with the waves easily.
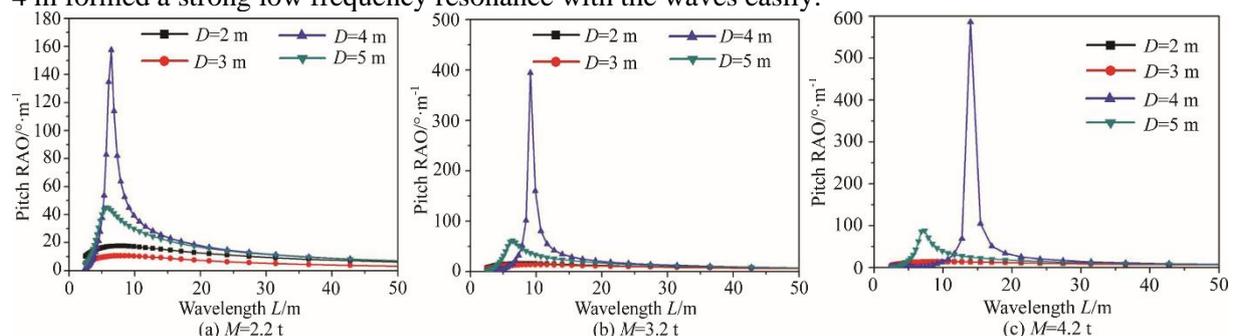

Figure 3. Relationship between the buoy diameter and wavelength in resonance state

Combined by the aforementioned analysis, it was evident that the maximum pitch RAO of the buoy was obtained at the buoy with the mass 4.2 t and the diameter 4 m. Therefore, according to the hydrological environment, designing the corresponding buoy diameter was another way to achieve the optimal capture power of the buoy by realizing the resonance between the buoy and waves.

3.3. Applicability analysis of the buoy

It was obvious that the pitch response of buoy was affected by the SBWEC mass, buoy diameter and wavelength, simultaneously. Then it was surmised that there was an optimal buoy structure that can achieve a greater capture power in the low energy density sea areas. Therefore, the applicability

analysis was carried out to search the suitable buoy mass and diameter for the Shandong Peninsula using the orthogonal experiment. The factor level value was represented in the Table 2.

Table 2. The factor level table

Factor / Level	A Mass×10^3/Kg	B Diameter/m	C Wavelength/m
1	2.2	2	14
2	3.2	3	10
3	4.2	4	7
4	4.2	5	14

The orthogonal experiment was arranged in accordance with $L_{16}(4^5)$ based on the Table 2 and the results were recorded in Table 3. The maximum capture power was the ultimate goal of the buoy optimization. It was derived that the maximum range of the factor C, B and A were 30.71, 25.58 and 23.02, respectively, showing the decreasing influence on the capture power. Therefore, it was indicated that the wavelength was the most significant factor to affect the design of wave energy converter. Among them, the value of 130.55 corresponding to the first level of the factor C was the largest, indicating the first level was the best. At the same way, the third levels of the factor B and A were the best, respectively. Through the above analysis, the test results shown that the best combination scheme was $A_3B_3C_1$.

Table 3. The orthogonal test record

Factor / Number	1 A		2 B	3 C		Test index results
1	1	1	1	1	1	109.85
2	1	1	2	2	2	81.00
3	1	1	3	3	3	97.01
4	1	1	4	4	3	83.24
5	2	2	1	2	2	90.27
6	2	2	2	1	1	158.88
7	2	2	3	4	3	98.30
8	2	2	4	3	3	100.68
9	3	3	1	3	3	99.33
10	3	3	2	4	3	110.40
11	3	3	3	1	1	149.46
12	3	3	4	2	2	104.00
13	4	3	1	4	3	99.33
14	4	3	2	3	3	110.40
15	4	3	3	2	2	149.46
16	4	3	4	1	1	104.00
K_1		371.1	398.78	522.19		
K_2		448.13	460.68	424.73		
K_3		926.38	494.23	798.69		
K_4			391.92			
k_1		92.78	99.70	130.55		
k_2		112.03	115.17	106.18		
k_3		115.80	123.56	99.84		
k_4			97.98			
Range		23.02	25.58	30.71		
Optimization		A3	B3	C1		

4. Conclusion

Based on the characteristics of the low wave energy density seas, the interaction among the buoy mass, diameter and wavelength was studied using the hydrodynamic computing software AQWA. Then, orthogonal experiment was carried out to study the applicability of the wave energy converter in Shandong Peninsula. The following conclusions were obtained,

(1) As the mass increases, the wavelength reaches its maximum at SBWEC mass 4.2 t and was most sensitive to the variation in the mass when the buoy diameter is 4 m.

(2) The wavelength in the resonance state gradually increased with the increasing of buoy diameter and then decreased when the mass of the buoy was constant. The maximum pitch RAO of the buoy was obtained at the buoy diameter of 4 m.

(3) Applicability analysis denoted that the SBWEC with the mass of 4.2 t and the buoy diameter of 4 m was suitable for the Bohai Sea and the north of the Yellow Sea, especially in the Bohai Strait to obtain the maximum capture power of 150 W owing to the wavelength of 14 m.

Acknowledgement

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