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Optimization of wave energy capture of wave-powered navigational lighting buoys of seadromes

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Abstract: [Objectives] This paper proposes an optimized design for wave-power navigational lighting buoys of seadromes. **[Methods]** Based on the theory of three-dimensional potential flow, the buoyant motion response of a buoy is calculated. A type of array of wave-power navigational lighting buoys located in an offshore seadrome is proposed, and a procedure for the design optimization of its component buoys is presented. Matching the best Power Take-Off (PTO) damping, the diameter to draft ratio and array distance with the best energy capture width ratio are acquired, and the energy capture for the short-term forecast of the buoy array is accomplished. On this basis, combined with the actual sea conditions, energy capture for the long-term forecast of an individual buoy is accomplished. The influence of the buoy diameter, buoy draft and array distance on the energy capture width ratio is discussed. **[Results]** The results show that the energy capture width ratio is at its greatest when the diameter to draft ratio is between 2.4 - 2.6; the smaller the distance between array buoys, the greater the energy capture width of each buoy. **[Conclusions]** The results can provide a reference and suggestions for the optimization of the design of wave energy generation for arrays buoy.

Key words: array buoy; PTO damping; energy capture width ratio; seadrome

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0 Introduction

The construction of seadrome is of great importance to the development of general aviation. Navigational lighting buoys with indicating functions are usually arranged on both sides of the harbor channel and the airport runway in the process of constructing seadrome along coastal areas. And there is a certain distance between the buoys to form array buoys, the scale of which will not be too large. Light buoys deployed in the sea need to set up lines from the coast to transport power. If they are designed as oscillating buoy wave-energy converting device, the self-generating power function of the buoy can be realized for its own power needs, which is of great significance for the construction of seadrome, in particular, for the power transmission of light buoys in remote seas.

Oscillating buoy wave-energy converting device is a kind of energy device which uses buoy in the water as wave energy absorption carrier, and then converts the energy absorbed by the buoys into power through power take-off (PTO)[1]. Oscillating buoy wave-energy converting device has the advantages of small construction difficulty and high efficiency, suitable for large-scale power generation arrangement, among which array arrangement is an effective application. However, due to the large scale, there are problems of installation and stability of power generation, so the array-type wave power generation devices are rarely applied at present. But array buoys are still the research trend of oscillating buoy wave-energy converting device. Compared with a single buoy, the

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effect of buoy distance on overall energy capture often needs to be considered in numerical simulation analysis due to the mutual interference among buoys in array-type arrangement.

Many studies have been carried out on an array-type wave energy generation device both in China and abroad. Ringwood et al.[2] used WAMIT to calculate and analyze the whole system of oscillating buoy wave energy generation device, including the optimization of buoy and PTO configuration, and discussed the effect of buoy arrangement on wave energy capture. He et al.[3] carried out a hydrodynamic analysis of an array-type wave energy generation device, and discussed the effect of scale and wave direction on the power generation stability of the wave energy generation device. Gou et al.[4] carried out tests on a simple array of wave energy generation devices to prove that the device without secondary conversion can still guarantee the stability of power generation and improve energy conversion efficiency. Gu et al.[5] studied the hydrodynamic performance of an array-type wave energy generation device and conducted sea trials, which provided basis for further optimization of the device. It can be seen that the majority of existing oscillating buoy wave-energy generation devices are mainly for the capture and utilization of wave energy in deeper waters, which are generally used for wave energy generation with large-scale trend. For shallow sea areas, oscillating buoy wave-energy generation device is seldom used, which is designed with miniaturization due to characteristics of wind waves in shallow waters. There are few studies on the optimization of miniaturized array-type wave energy generation device at present. In this paper, for the first time, navigational array buoys of seadrome in shallow waters are taken as the research object to optimize the wave energy capture of light buoy. Besides, the buoy arrays are simplified into prototypes of oscillating buoy wave-energy generation device for the study of wave energy capture. The buoy can capture wave energy through heaving oscillation and convert it into power energy by the energy conversion device for its own power generation. Based on engineering requirements, an optimization method of energy capture is proposed, that is, the energy capture width ratio is taken as an indicator for energy capture to analyze the effect of buoy shape and distance on energy capture of array-type wave-powered navigational lighting buoys, and the energy capture width ratio is predicted for a long time to maximize the energy capture of array-type wave-powered navigational lighting buoys and provide practical reference for the further optimization and design of such array-type light buoys and the construction of seadrome.

1 Device introduction

Fig. 1 shows the arrangement of array buoys. According to seadrome construction requirements, the minimum buoy distance of 10 m is required to act as a safe distance for the buoy against collision in actual operation. The water depth of the sea where seadrome is located is 5.5 m, and the wave condition is moderate. The buoy is a small light buoy, and the schematic of single wave energy converter is shown in Fig. 2 [6]. The basic shape of the buoy can be regarded as a cylinder, which is connected with the energy conversion device through connecting rod and moored to the seabed. A direct-driven generator is used for energy conversion, and the buoy moves vertically in the wave. The buoy drives the generator to generate power for its own buoy lights.

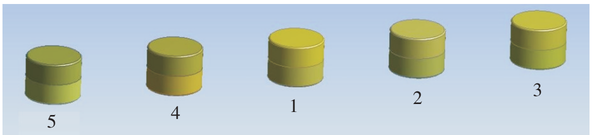

Fig.1 Arrangement of array-buoy

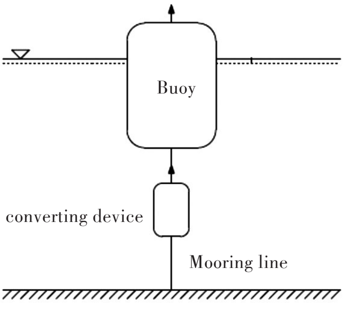

Fig.2 Schematic of single wave energy converter

2 Equation of buoy motion

This paper mainly discusses the capture of wave energy by the vertical movement of the buoy. The movement of the buoy in the wave is calculated based on the theory of three-dimensional potential flow. The vertical motion equation of the buoy is

$$(M+M_a)\ddot{Z}+N\dot{Z}+CZ=F_w \tag{1}$$

where Z is the vertical displacement; M is the buoy mass; M_a is the added mass; N is the damping coefficient; C is the hydrostatic restoring force coefficient; F_w is the wave excitation force.

F_{PTO} is exerted on the buoy due to the PTO. According to References [7–8], when direct–driven generator is used as the PTO of the wave–energy device, only PTO damping force contributes to the conversion of wave energy, which can be treated as a linear damping. Then the damping force acted on the buoy by the energy conversion system is

$$F_{\mathrm{PTO}}(\omega)=-b_1\dot{Z}(\omega) \tag{2}$$

where b_1 is the PTO damping coefficient; ω is the frequency.

The heaving oscillation equation in the frequency domain is

$$[-\omega^2(M+M_{\mathrm{a}}(\omega))+\mathrm{i}\omega(b_1+N_1(\omega))+\rho g A_{\mathrm{w}}]Z(\omega)=F_{\mathrm{w}}(\omega) \tag{3}$$

where N_1 is the damping coefficient of heaving oscillation; ρ is the density of seawater; g is the gravitational acceleration; and A_{w} is the water plane area of buoy. Let $H(\omega)$ be the frequency response function for the heaving oscillation of buoy, then there is

$$H(\omega)=\frac{F_{\mathrm{w}}(\omega)/A}{-\omega^2(M+a_{\mathrm{m}}(\omega))+\mathrm{i}\omega(b_1+R(\omega))+\rho g A_{\mathrm{w}}} \tag{4}$$

where A is the incident wave amplitude; a_{m} is the added mass of heaving oscillation; R is the natural damping coefficient of heaving oscillation. The frequency response function of heaving oscillation can be numerically calculated by the AQWA, a three–dimensional potential flow theory software.

3 Energy capture

3.1 Energy capture width ratio

In order to conduct long–term forecast for the energy capture of an array–type wave energy generation device in the operation sea area, the energy capture width ratio is introduced as an indicator to measure the energy capturing ability of the device during the study. The energy capture width ratio (CWR) is an important parameter to describe the energy capture efficiency of wave energy devices, which is defined as the ratio of buoy–to–energy captured power to the wave input power in buoy width[9]:

$$CWR=\frac{P}{DQ} \tag{5}$$

where P is the energy capture power of the device in the wave; Q is the wave input power in the width of buoy; D is the buoy width, namely the buoy diameter. The Q is the power that passes the section of unit width perpendicular to the wave propagation direction in the unit time. According to the linear wave theory, the energy transport of wave energy is[9]

$$Q=\rho g\int_0^{\infty}v_{\mathrm{g}}(\omega,h)S(\omega)\mathrm{d}\omega=\rho g\sum_{i=1}^{N}v_{\mathrm{g}}(\omega_i,h)S(\omega)\Delta\omega_i \tag{6}$$

where v_{g} is the wave group velocity; $S(\omega)$ is the wave spectrum density; ω_i is the i^{th} frequency for discrete calculation; and h is the water depth.

$$v_{\mathrm{g}}(\omega,h)=\frac{g}{2\omega}\tanh(kh)\left[1+\frac{2kh}{\sinh(2kh)}\right] \tag{7}$$

where k is the wave number. The energy capture power P_i of the device is[8]:

$$P_i=\frac{1}{2}b_1\left|\dot{Z}_i\right|^2 \tag{8}$$

where $\left|\dot{Z}_i\right|$ is the velocity amplitude of heaving oscillation of the buoy in the i^{th} frequency wave, which is obtained by solving the equation of motion. The damping coefficient of the energy conversion system b_1 is constant, irrespective of the external wave frequency. The total capture power of the buoy is as follows:

$$P=\sum_{i=1}^{m}P_i=\sum_{i=1}^{m}\frac{1}{2}b_1\left|\dot{Z}_i\right|^2 \tag{9}$$

where m is the total number of wave frequencies.

3.2 Optimal PTO damping coefficient

Different PTO dampings correspond to different buoy capture powers. From Eq. (5), it can be seen that the capture power has a linear relation with PTO damping coefficient b_1 and has a square relation with the velocity of the heaving motion. When calculating the optimal PTO damping coefficient, a series of PTO damping coefficient values b_1 can be substituted respectively into equations of buoy motion to obtain the velocity of heaving oscillation, and substituted into Eq. (5) to obtain the energy capture power at each damping coefficient b_1. The optimal PTO damping coefficient is always a certain value for a buoy with given scale[8]. Fig. 3 shows curves of energy capture power changing with PTO damping coefficient when buoy diameter is D = 2.8 m and draft is d = 1.5 m, where the abscissa corresponding to the peak of the curve is the optimal PTO damping coefficient, and the ordinate corresponding to the peak is the maximum power that can be captured under the optimal PTO damping.

3.3 Forecast of energy capture

For long–term operation of array buoys in the sea, long–term sea conditions must be monitored statistically, with short–term and long–term forecasts on measured sea condition data or wave scatter dia-

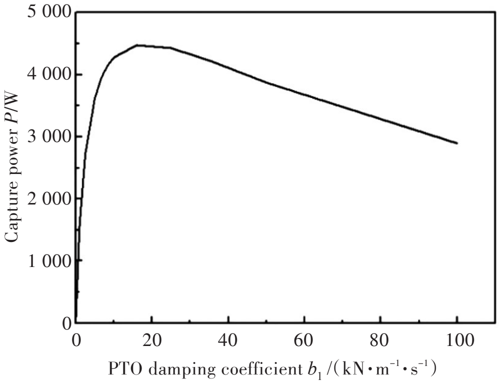

Fig.3 Variation of power capture with respect to PTO damping coefficient b_1 when diameter is D =2.8 m and draft is d =1.5 m

grams to predict the energy capture of devices. For single buoy or array buoys, long-term forecast of energy CWR can refer to the following equation

$$CWR = \sum_{n=1}^{N} p_n \cdot CWR_n \tag{10}$$

where p_n is the probability of occurrence of each sea condition; CWR_n is the energy CWR under n^{th} sea condition, which can be obtained from Eq. (5); and N is the number of typical sea conditions.

3.4 Optimization process

The optimization process of array buoys is established as shown in Fig. 4, which can be applied to forecast energy CWR in different sea areas based on actual sea conditions. In the process of optimizing array buoys, the outer dimensions of a single buoy are selected firstly, and then the energy CWR of heaving oscillation for buoys with different scales under different sea conditions is calculated. Next, a short-term forecast on the energy capture of a single buoy is carried, and afterwards long-term forecast for energy capture of array buoys is made according to the wave scatter diagram or other measured wave data. Finally, the best scale which meets engineering requirements is selected, including diameter and draft (or diameter-to-draft ratio).

Based on the optimization for dimensions of single buoy, the distance between array buoys is adjusted, and long-term and short-term forecasts for total energy CWR of array buoys are made to maximize the energy CWR.

4 Numerical simulation and analysis

4.1 Model parameter settings

Array buoys are arranged in five buoys. In the process of optimizing the shape of single buoy, the energy CWRs at different diameters of draft (diameter-to-draft ratio: D/d = 1.2-6.0) are discussed, and the effect of diameter and draft on energy CWR of buoys is analyzed separately to get the best scale. Based on the optimization for shape of single buoy, the energy CWRs of an array-type wave energy generation device under different buoy distances (10-14 m) are calculated, and the optimal distance value is obtained by comparative analysis. The parameter variation of diameter and draft is shown in Table 1.

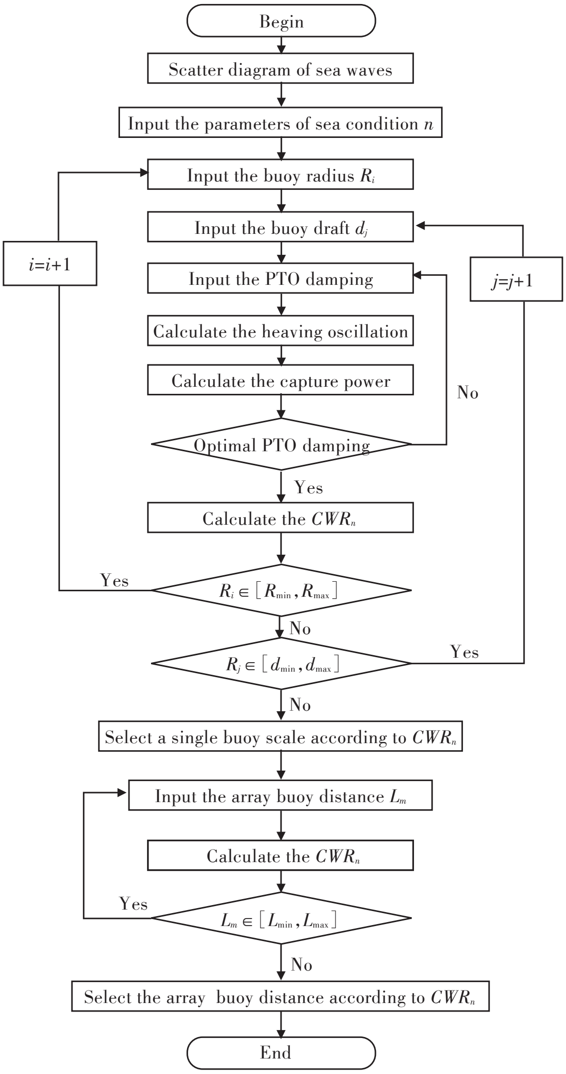

Fig.4 Design optimization process for main dimensions of array buoy

Table 1 Parameters variation of diameter and draft

Diameter D/m	Draft d /m
2.0, 2.4, 2.8, 3.0, 3.2, 3.6, 4.0	1.0
4.0	1.0, 1.5, 2.0, 2.5, 3.0

4.2 Sea conditions of work area

The sea conditions of work area are usually expressed in the form of wave scatter diagrams. The real-time measurement and statistics for perennial data parameters of sea wave are required. The wave parameters and the probability of occurrence may also be used to represent sea conditions in the absence of actual measured data. The wave conditions in the coastal waters are relatively stable, and seadromes are generally located in areas with small waves[10]. Under several typical sea conditions as shown in Table 2, the energy CWRs of the devices are respectively calculated, and the long-term forecast is made based on the occurrence probability of sea conditions[11].

Table 2 Sea states of work area

Sea condition	Significant wave height $H_{1/3}$/m	Zero-crossing period T_z/s	Occurrence probability/%
1	0.35	3.6	12
2	0.36	4.0	13
3	0.24	3.2	14
4	0.27	2.8	20
5	0.30	3.0	17
6	0.22	4.3	16
Others	–	–	< 8

4.3 Effect of diameter-to-draft ratio on energy CWR

The energy CWR for the buoy at each diameter and draft is calculated under sea conditions given in Table 2, as shown in Fig. 5. It can be seen from the figure that with the optimal PTO damping coefficient, the energy CWR increases first and then decreases with the increase of diameter-to-draft ratio and reaches the maximum at diameter-to-draft ratio of 2.4-2.6.

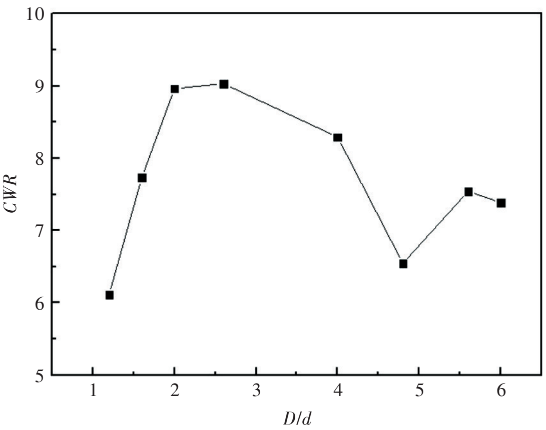

Fig.5 Variation of energy capture width ratio with respect to diameter draft ratio

4.4 Influence of buoy diameter on energy capture

In order to study the impact of buoy diameter on the energy CWR, the capture power P in different diameters when draft d = 1 m is calculated, and variations of capture power with respect to PTO damping coefficient b_1 is shown in Fig. 6. As can be seen from Fig. 6, the larger the diameter of the buoy is, the better the PTO damping coefficient corresponding to the buoy is. And the total capture power of buoy is also greater with the optimal PTO damping coefficient.

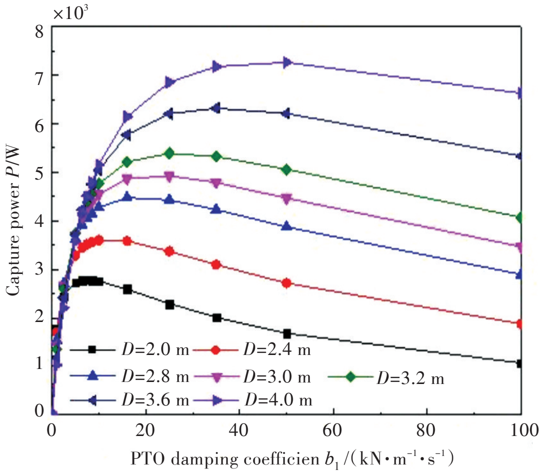

Fig.6 Variation of power capture with respect to PTO damping coefficient b_1 in different diameters when draft d=1.0 m

Fig. 7 shows the variation of energy CWR of buoys with respect to wave period T in different diameters when draft d = 1 m with the optimal PTO damping coefficient. The peak value of variations in the figure shows the maximum wave energy absorption that can be achieved in the peak corresponding to the wave period at this size. The buoy with different diameters will decrease with the decrease of its diameter. According to the short-term forecast of energy CWR, when wave period T > 3 s, the larger the diameter of the device is, the greater the energy CWR is. However, when T < 3 s, the wave energy capture is slightly larger.

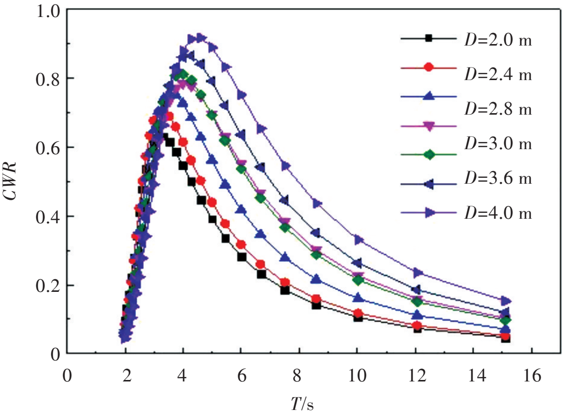

Fig.7 Variation of energy capture width ratio with respect to wave period in different diameters when draft d=1.0 m

Combining Fig. 6 and Fig. 7, it can be seen that for buoys with small diameter, the level of energy capture mainly depends on the optimal PTO damping coefficient, that is, PTO damping coefficient b_1 plays a dominant role in Eq.(8). Under the same draft, buoys with larger diameter have higher energy capture efficiency.

4.5 Influence of buoy draft on energy capture

Similarly, the buoy capture power P under different drafts is calculated when the diameter is D = 4 m. The variation of capture power with respect to PTO damping coefficient b_1 is shown in Fig. 8, from which it can be seen that the larger the draft is, the smaller the optimal PTO damping coefficient is. And the total buoy capture power is smaller with the optimal PTO damping coefficient. Fig. 9 shows the variation of energy CWR with respect to the external wave period T in different drafts when diameter is D = 4 m. The peak value of buoys with different draft depths increases with the increase of draft. According to the short-term forecast of energy CWR, when the external wave period T = 4.2–6 s, the larger the draft is, the greater the energy CWR is. While for the case of gentle wave conditions in coastal water ($T < 4$ s), the draft is beneficial for energy capture.

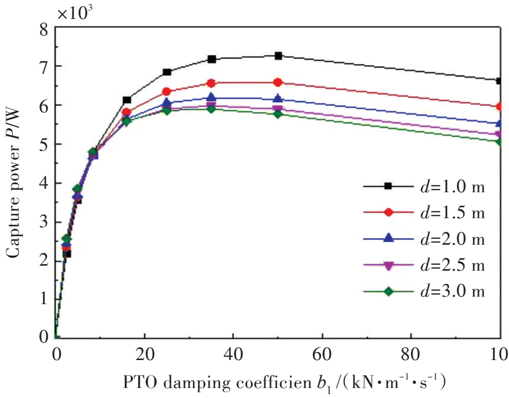

Fig.8 Variation of power capture with respect to PTO damping coefficient b_1 in different drafts when diameter D=4.0 m

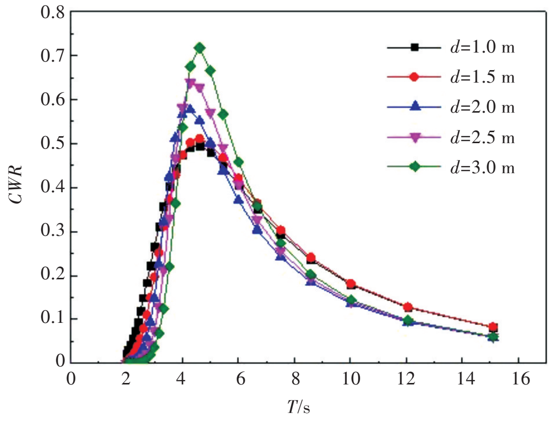

Fig.9 Variation of energy capture width ratio with respect to wave period in different drafts when diameter D=4.0 m

It can be seen from Fig. 8 and Fig. 9 that under the condition of $T < 4$ s or $T > 6$ s, the optimal PTO damping coefficient becomes dominant under the same diameter. However, when the external wave period $T < 4$ s, the heaving velocity which is a quadratic term in Eq. (8) has a greater influence.

4.6 Influence of buoy distance on energy capture

Fig. 10 shows the variation of energy CWR of each buoy (buoy number shown in Fig. 1) with respect to distance between array buoys in the sea conditions of work area shown in Table 2. We can see that the CWR of No. 3 device increases with the increase of the buoy distance under the sea conditions; while the rest of buoys tend to drop first and then rise. The No. 2 device has the smallest CWR when the buoy distance is 13.0 m, and No. 1 device achieves the minimum when the buoy distance is 12.0 m. The CWR of No. 4 and No. 5 devices is the minimum when the buoy distance is 12–13 m, while the maximum CWR is in the buoy distance of 10.0 m.

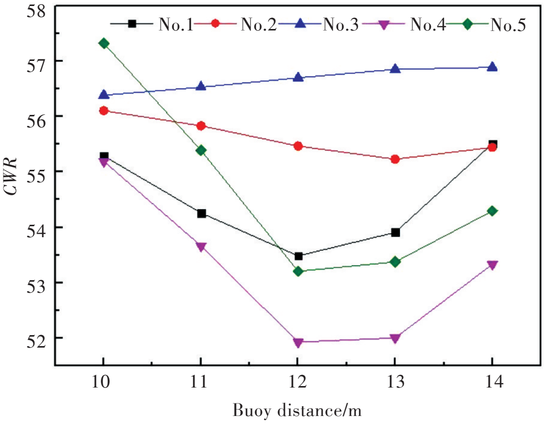

Fig.10 Variation of energy capture width ratio of each buoy with respect to distance between array-buoy

Fig. 11 shows the variation of total energy CWR of array buoys with respect to buoy distance. It shows that the total energy CWR of array buoys tends to decrease first and then increase with the increase of buoy distance under the sea conditions, and the minimum value appears in the buoy distance of 12–13 m. When the distance between buoys is 10–12 m, in order to ensure the maximum CWR, the smaller buoy distance is better, that is, the smaller the buoy distance is, the more obvious the interaction between the buoys is, which is better for energy capture. The calculation of the energy CWR is based on the exist-

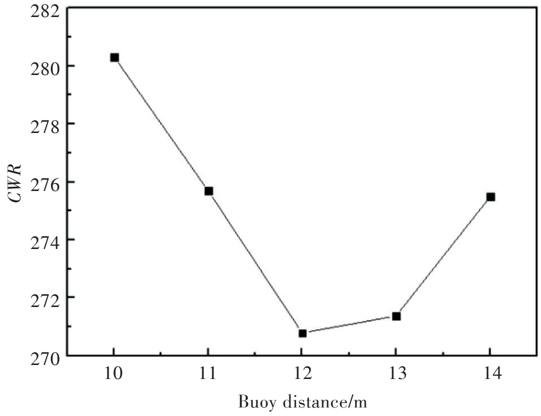

Fig.11 Variation of total energy capture width ratio of array-buoy with respect to distance between buoy

ing sea conditions of the work sea area shown in Table 2, and the buoy distance with the highest capture capacity is also different under different sea conditions.

5 Conclusions

In this paper, the hydrodynamic design of wave-powered navigational lighting buoys used for seadrome is optimized. The influences of buoy diameter, draft and buoy distance on buoy energy capture are analyzed respectively, which provides a reference for the design and optimization of array-type wave power generation devices and has certain reference meaning for the buoy design in the construction of seadrome. The main conclusions of the paper are as follows.

1) To maximize energy capture, the optimal diameter-to-draft ratio of the buoy should be between 2.4-2.6 (since the diameter and draft are different for the required size of different projects, the diameter and draft given in this paper can be taken as a reference for designing the buoy), and the best energy capture is achieved when the distance between array buoys is 10 m on the basis of meeting the engineering requirements of seadrome construction.

2) For a single buoy, the larger the diameter of the buoy, the greater the corresponding optimal PTO damping coefficient is, and the higher the capture efficiency is; the larger the draft is, the smaller the corresponding optimal PTO damping coefficient is. The waves in coastal waters are mainly short waves with short wave periods, whereas buoys with smaller draft have higher energy CWR than others.

3) For array-type buoy generation device, the smaller the buoy distance is, the more obvious the effect of buoy interaction on the heaving oscillation is, and the better the energy capture is. When the array buoy is used for the seadrome, the energy CWR of array buoys is the largest when the buoy distance is 10 m.

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[*Continued on page* 37]

内压下矩形耐压舱内部结构优化设计

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摘　要:[**目的**]为有效降低内压下矩形耐压舱板架弯曲应力,[**方法**]分别提出内压下矩形耐压舱内部平台位置和支柱布局以及尺寸优化设计数学模型。以内部平台垂向位置作为设计变量,极小化横纵舱壁结构的最大弯曲应力,采用遗传算法求解,得到最优的内部平台布置位置,其优化结果接近垂向均布。支柱设计采用分级优化设计方法,先以等刚度支柱位置作为设计变量,极小化顶甲板结构的最大弯曲应力,分别得到不同支柱数量下的最优布局方案;然后依据应力约束条件选取支柱数量及布局,在此基础上进一步以支柱截面尺寸作为设计变量,以基础优化方案的重量作为约束,极小化顶甲板结构的最大弯曲应力,得到不等刚度支柱最优截面尺寸。[**结果**]其优化结果显示偏中心区域支柱截面积更大。最终优化设计方案较初始方案,横舱壁、纵舱壁和顶甲板弯曲应力分别降低了28.3%,25.7%和13.9%。[**结论**]本优化设计方法可为类似结构设计提供方法参考和设计借鉴。

关键词:内压矩形耐压舱; 优化设计; 内部平台; 支柱布局

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水上机场助航波能灯浮标的波能俘获优化

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摘　要:[**目的**]为了对水上机场波能灯浮标进行设计优化,以工作于沿海水上机场的阵列式助航波能灯浮标为研究对象,提出一种小型阵列式浮标的优化设计方法。[**方法**]基于三维势流理论,计算浮标的垂荡运动响应,在满足最佳能量转换部分(PTO)阻尼匹配的情况下,得到使能量俘获宽度比最大的浮标直径吃水比和浮标间距,然后对单个浮标的能量俘获进行短期预报,并在此基础上结合实际海况对阵列式浮标的能量俘获进行长期预报,分别讨论浮标直径、吃水和浮标间距对阵列式浮标能量俘获的影响。[**结果**]结果表明,当单个浮标直径吃水比为2.4~2.6时,能量俘获宽度比最大;阵列浮标间距越小,阵列式助航波能灯浮标的能量俘获宽度比越大。[**结论**]所做的工作可为阵列式波浪能发电装置的设计优化提供一定的参考和建议。

关键词:阵列式浮标; PTO阻尼; 能量俘获宽度比; 水上机场