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Performance evaluation of a dual resonance wave-energy convertor in irregular waves

Zhongfei Chen[a], Binzhen Zhou[a,b,*], Liang Zhang[a,*], Liang Sun[c], Xuewei Zhang[a]

[a] College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China
[b] Key Laboratory of Renewable Energy, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Guangzhou 510640, China
[c] School of Transportation, Wuhan University of Technology, Wuhan 430063, China

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ABSTRACT

A new waterproof point absorber, named Dual Resonance wave-energy convertor (DR-WEC), is put forward in this paper. A geometry with low viscous effect is adopted for the waterproof outer floater of DR-WEC and two resonance frequencies can be found due to the existence of two sets of mass-spring subsystems. The motions and absorbed power of the DR-WEC in regular and irregular waves are investigated using the linear wave theory and the spectral analysis method with viscous effect being considered. The influence of three mechanical parameters, i.e., the internal mass, stiffness of spring and damping of power-take off (PTO) system, on the capture width ratio is studied. The mechanical parameters can affect the shapes of power response curves, which bring the possibility to enhance the wave power absorption by manipulating these parameters according to the characteristics of encountered waves. The Generalized Pattern Search (GPS) algorithm is employed to find these optimal mechanical parameters in both short-term and long-term sea states. The numerical results have confirmed that not all of the three mechanical parameters are needed to vary during operation. Some of the three parameters can be fixed for the balance of cost efficiency and wave power absorption. When the number of variable mechanical parameters is two, one, and zero, declinations of the annual average power relative to that with three are 4.1%, 13.0%, and 36.4%, respectively. At last, solutions for realizing an internal parameter-variable mechanism are discussed.

1. Introduction

Wave energy is one of the most promising renewable energy in the ocean because of its high energy density, predictability and availability [1]. The total amount of the exploitable wave energy is around 2TW, which can almost meet the energy demand of the whole world in 2008 [2]. The first wave energy device is invented by Girards in 1799 [3] and many concepts have been proposed [4]. Generally, wave energy convertors (WECs) can be divided into three categories [5], i.e., point absorber, attenuator, and terminator. Comprehensive literature reviews can be found in [3–5], etc. It has been proven that the point absorber is the most effective in terms of power absorption per unit volume [6]. However, a point absorber, which can usually achieve the favorable absorption efficiency around the resonant frequency, is sensitive to the wave frequency [7]. In real sea states, the wave encounter frequency is changing all the time in different time scales (minutes, hours, days, etc.) [8]. It is hard for a point absorber to operate with high efficiency in a wide range of frequencies. Moreover, the operational environment for WECs is usually harsh in the open sea [9], in terms of extreme waves, corrosion, bio-attachment, etc.

Aiming at the two challenges mentioned above, a new concept of point absorber, the DR-WEC (Dual Resonance WEC), is proposed in this paper. As shown in Fig. 1, the DR-WEC is a two-body point absorber. Different from classic devices, such as OPT PowerBuoy [10], L10 Buoy [3], Mark 3 PowerBuoy [5], and Wavebob [11], the second body of the DR-WEC is contained inside a waterproof outer floater, and connected with the internal spring and the generator. These three parts comprise the internal power-take off (PTO) system. By manipulating parameters of the PTO system, the DR-WEC is able to adapt to different wave environment to enhance the wave power absorption ability. The aimed wave environment in this paper is the short-term sea state which normally last 0.5–10.0 h [8]. Furthermore, the DR-WEC is fully waterproof, similar to the SEAREV [12] and Frog [13], which contains all the fragile moving mechanical parts inside to make it survive in the open sea more easily. The DR-WEC also has the potential to dive into the water to avoid violent environmental impacts in extreme weather.

The performances of WECs are highly different in regular and irregular waves. Gomes et al. [7] studied a bottom-hinged plate WEC in

* Corresponding authors at: College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China.
E-mail addresses: zhoubinzhen@hrbeu.edu.cn (B. Zhou), zhangliang@hrbeu.edu.cn (L. Zhang).

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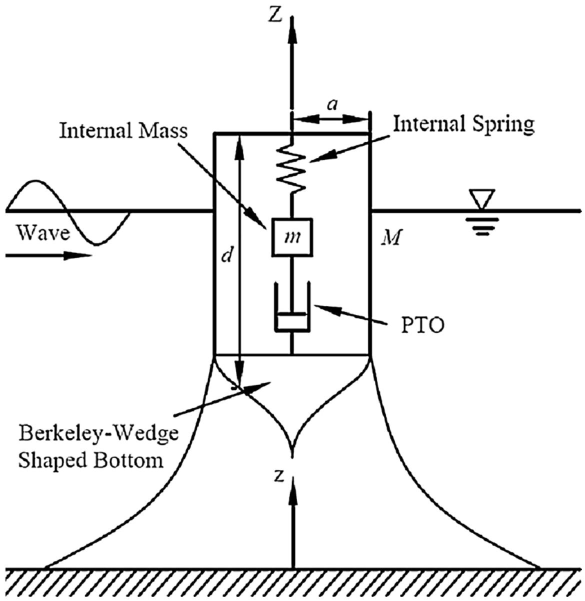

Fig. 1. Schematic of a DR-WEC concept.

both regular and irregular waves. A suggested geometry for irregular waves was presented with the consideration of the fluid viscosity and some nonlinear effects. Rahmati and Aggidis [14] analyzed a point absorber in irregular waves numerically and experimentally. They concluded that the numerical results in regular waves only provide an upper estimation of the power absorption. Gómez et al. [15] asserted that the maximum instantaneous power absorbed by a submerged point absorber in irregular waves could be 15–20 times larger than the mean power which is only 10–20% of that in regular waves. In addition, waves in the open sea are mainly irregular waves [8]. Thus, even though the analysis in regular waves can provide more general results and design principles, the study of the performance evaluation for a WEC in irregular waves is more practical.

In the present paper, the optimization of power absorptions in irregular waves are conducted by the Generalized Pattern Search (GPS) algorithm [16], which is capable of finding the local optimal value for a multi-variable function without the need of derivative calculation. After decades of development, the GPS algorithm can deal with the optimization problem with boundary constraints, linear constraints, and nonlinear constraints, etc. [17]. Compared with other optimization algorithms, such as genetic algorithm, simulated annealing, etc., the GPS method has advantages in calculation speed and precision, but cannot deal with the global optimization problem with multiple local maxima [17,18]. For our problem, there is only one optimal value, i.e., the local optimum equals to the global optimum (shown in Section 4.2).

Firstly, this paper proposes a new concept of WEC, the DR-WEC, with features of dual resonance, waterproof floater with build-in PTO, and low viscous effect geometry. Secondly, characteristics of the motion and power responses of the DR-WEC are investigated in both regular and irregular waves. Moreover, the power output in irregular waves is optimized in both short- and long-term sea states by the nested application of the GPS method. Finally, possible solutions for internal variable-parameter mechanism are discussed.

2. Concept of the DR-WEC

As illustrated in Fig. 1, the outer floater of DR-WEC consists of two parts, namely, the upper cylinder connected with the lower Berkeley-Wedge (BW) shaped bottom. The Berkeley-Wedge (BW) is a 2D shape developed by Madhi et al. [20] at University of California, Berkeley, which can minimize the viscous damping in heave mode to improve the power absorption. In present concept, the outer floater can be fully waterproof so that the PTO mechanism inside is well protected.

There are two sets of mass-spring-damper subsystems in the DR-WEC (shown in Fig. 1). The first is the mechanical system of the internal PTO, including an internal mass m, an internal spring with stiffness k_m, and a PTO damper with damping coefficient B_g. The second subsystem is the outer floater including the mass of the outer floater M-m (where M is the total mass of the whole DR-WEC system, m is the internal mass), hydrostatic restoring forces on the outer floater with stiffness $C_3 = \rho g \pi a^2$ (where $\rho = 1025\,\mathrm{kg/m^3}$ is the water density, $g = 9.81\,\mathrm{m/s^2}$ is the gravitational acceleration, a is the radius of the outer floater), and the hydrodynamic damping $\lambda_{T.}$ in heave mode with viscous effect considered. There are two resonant frequencies for the DR-WEC due to the existence of these two sets of mass-spring-damper subsystems, which is the reason of the "Dual Resonance (DR)" in the name. For a floating structure, parameters of the second one are determined by the geometry of the wetted surface. The outer floater of a point-absorber is normally a rigid body. Practically, once the outer floater is constructed, it is hard to change the geometry. Moreover, the PTO system is inside the waterproof floater, which brings the possibility of varying these three mechanical parameters by certain mechanisms according to the wave environment to enhance the wave power absorption ability. Feasibilities of internal variable-parameter mechanism are discussed in Section 5.

The non-dimensional mechanical parameters of the internal PTO are defined as follows: the spring ratio $\bar{s} = k_m/C_3$, the mass ratio $\overline{m} = m/M$ and the damping ratio $\overline{B}_g = B_g/\lambda_T$, where $\lambda_T = (1 + f_{vis})\lambda_{33}$ is the total damping with viscous effect considered, and λ_{33} is the potential radiation damping. From the experimental study [21] conducted at the UC Berkeley Richmond Field Station (RFS) with the coexistence of multiple degree of freedoms (not pure heave), it is found that $f_{vis} \approx 3.0$ for a pure cylinder and $f_{vis} \approx 0.6$ for the BW, which revealed that the BW has smaller viscosity.

3. Motion and power response

The experiment of Son et al. [22] demonstrated that pitch and surge have little effect on the performance in heave for a point absorber working in heave mode. Thus, in the present paper, we only consider the heave motion which is the working degree of freedom. Bachynski et al. [23] argued that a slack mooring system only affected the pitch and surge motions at a very low frequency and had little influence on the heave motion for a point-absorber. Thus, the effect of mooring system of DR-WEC is neglected in the present analysis. By numerical study and experiment validation, Zurkinden et al. [24] proved that the linear potential wave theory with viscous damping correction is a good approximation for the prediction of motion and power responses of point absorbers in operational sea states (irregular waves). Therefore, in this study the linear potential wave theory is adopted. By the experimental study, Viray [21] revealed that the viscous effect is mainly associated with the damping term, while the added mass and the excitation force are almost the same as the prediction of the potential theory. Consequently, the viscous effect of the outer floater is considered by the viscous correction which derived from the experiment [21].

All the hydrodynamic forces are calculated by AQWA in frequency domain which is based on the boundary element method (BEM). Under the assumptions of an incompressible and inviscid fluid with irrotational motion, there exists the velocity potential φ which satisfies the Laplace equation, i.e.

$$\nabla^2\varphi = 0 \tag{1}$$

$$\varphi(x, y, z, t) = \varphi_I + \varphi_D + \varphi_R \tag{2}$$

where φ_I is the incident potential which is usually known, φ_D is the diffraction potential, and φ_R is the radiation potential. φ_D and φ_R can be calculated by solving the derived boundary integral equations. The