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Experimental and numerical study on a novel dual-resonance wave energy converter with a built-in power take-off system

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A B S T R A C T

A new concept of point-absorber wave energy converter (WEC) with a waterproof outer-floater and a built-in power take-off (BI-PTO) mechanism, named Dual-Resonance WEC (DR-WEC), is put forward and investigated by experiments and numerical simulations. The BI-PTO mechanism includes spring, sliding-mass and damping systems, where the spring system is the most complicated and should be designed specially. A 1:10 scale model is designed. The mechanical performance of the BI-PTO system is investigated by a bench test. The results have shown that the design is feasible, and the added inertia effect of the BI-PTO has a negative influence on the power output. The average mechanical efficiency of the BI-PTO is 65.8% with maximum up to 80.0%. The motion and power responses of the DR-WEC are studied by a wave tank experiment and a linear numerical model with corrected mechanical added mass and viscosity. The viscous added mass and damping correction coefficients are obtained by a free decay test. The good agreement between the experimental measurements and numerical simulations has indicated that the present numerical model with corrections is of enough accuracy and the effects of mooring system and other degree of freedoms on the heave motion and power responses can be ignored.

1. Introduction

Wave energy is one of ocean renewable energy with huge reserves. Approximately, it could meet the electricity requirement of most countries that have enough coastline, if it is extensively exploited [1]. Generally, wave energy converter (WEC) techniques can be classified into attenuator, terminator, and point-absorber (PA) [2]. Extensive reviews can be found in Refs. [2–5]. A point-absorber WEC is convenient for array arrangement because of its small dimension relative to the encounter wavelength, and this type is very efficient in terms of wave-power absorption per unit volume [6]. These features make it perfectly suitable for the ocean areas with relatively low wave energy density such as the Chinese adjacent seas [7]. Even though, in these areas, the wave energy may not be sufficient enough to steadily supply the power for main-land grids, it could be an effective supplement for microgrids of islands, oil platforms, or other offshore marine structures [8].

There is one type of configuration of WEC that all power take-off (PTO) systems are built inside a water-proof outer-floater, such as, SEAREV (France) [9], Penguin (UK) [10], GyroPTO (Denmark) [11], and PS Frog Mk5 (UK) [12], etc. The wave energy is absorbed by the outer-floater and converted into mechanical energy, and then the PTO converts it to a more usable type of energy (e.g., electrical energy). Compared with many existing or proposed concepts that have moving mechanical parts immersed in the water, this kind of configuration could increase the reliability, reduce the difficulty of maintenance, and is good for the survivability in the harsh environments. The cost of a traditional point-absorber WEC is sensitive to the water depth, because it needs a fixed structure on sea-

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bottom or on shore as the reaction for the PTO. However, for a point-absorber WEC with a built-in PTO (BI-PTO), the PTO is built inside the outer-floater. Therefore, it is more cost-effective in term of water depth, because only a slacking mooring system is in need to overcome drift forces.

For a point-absorber WEC with a BI-PTO, the hydrodynamic properties of the outer-floater are relatively easy to compute, while the key issue is the design of a feasible BI-PTO system. The PTO consists of an inertial reaction body to form a relative motion with respect to the outer-floater. Generally, the internal reaction body has three types, namely pendulum (vertical or horizontal axis), gyroscope, and sliding-mass (see examples in Refs. [9–12]). The pendulum and gyroscope can work in pitch or roll only, and the gyroscope needs a high rotational speed which may be bad for the fatigue life of the system. The sliding-mass is working in the translational motion and the mechanical structure is relatively simple to design. The heave motion is more favorable for a point-absorber WEC because an axisymmetric out-floater can be applied to reduce the sensitiveness of wave directions. Therefore, the DR-WEC works in heave and adopts the sliding-mass as the internal reaction body.

The installing and testing of a WEC is difficult and expensive in the real marine environment, so that a device should be simulated and tested in small-scale first [13]. Ning et al. [14] tested a pile-restrained WEC-type floating breakwater. The wave energy capture ability and the breakwater ability were studied. A coaxial-cylinder WEC was studied experimentally and numerically by Son et al. [15]. Liu et al. [16] studied wave overtopping behaviors of a circular ramp overtopping WEC experimentally. An experiment of a 1:30 scale WaveCat was performed by Allen et al. [17], which formed the basis for future development and optimization. The key issue of a point-absorber WEC with a BI-PTO is the design of the PTO mechanism which is required to be tested and validated on the bench (which is normally a dry-test facility) first before testing of the whole system in the water, due to the complexity and the high cost of a PTO system [13]. The specialized test benches are able to simulate the wave excited motion of the outer-floater, so that the feasibility, reliability, and mechanical performance of PTOs can be validated and tested. Many researchers had conducted dry bench tests for PTOs. Dellicolli et al. [18] tested a permanent-magnet synchronous tubular linear generator for PA-WECs. The design and analysis were reported based on the experimental results on a rotating simulation test bench. Lasa et al. [19] designed and tested a hydraulic PTO on the bench to validate the dynamic performance. The experimental results were used for the improvement of an in-house numerical simulation model. Antolín-Urbaneja et al. [20] studied a hydraulic PTO device which consists of a double-acting hydraulic cylinder. The test results on the bench showed good correlations to that of the simulations.

In the present paper, a novel DR-WEC working in heave motion with a BI-PTO system is put forward. A sliding-mass is placed inside the outer floater and the relative heave motion between them makes the PTO system capture energy. The BI-PTO system composed of spring, sliding-mass, and damping systems is specially designed for the DR-WEC. A 1:10 scale model is constructed. A special bench test was firstly carried out to study the feasibility of the design and the mechanical performance of the BI-PTO system. Furthermore, the motion and power responses of the DR-WEC in regular waves are investigated by the experiment conducted in the wave tank at Harbin Engineering University. Meanwhile, a linear numerical model considering the mechanical added mass and viscous corrections is developed to study the hydrodynamic performance of the DR-WEC only in heave motion. The comparison with the experimental results is made to show the accuracy of the numerical model and the effect of mooring system and other degree of freedoms.

2. DR-WEC concept

The DR-WEC concept is demonstrated in Fig. 1. There are two sets of mass-spring-damping in the DR-WEC. The first is the mass of the outer-floater, spring of the hydrostatic restoring effect, and hydrodynamic damping of the floater. The second is from the PTO mechanism which is inside the outer-floater. Namely, the internal spring, the sliding-mass, and the damping of the generator. Because of the existence of these two sets of mass-spring-damping, the system has two undamped resonance frequencies. Therefore, we name this new WEC concept as the DR-WEC. The DR stands for the "Dual Resonance". By manipulating the parameters of the internal one can change these resonance frequencies. This gives a possibility that we can match the one of the resonance frequencies to the wave encounter frequency to enhance the wave power absorbing ability.

The outer-floater is axisymmetric to reduce the sensibility to wave directions. The conical bottom is to diminish the viscous dissipation, based on the research results in Ref. [21]. The radius and draft are a and d, respectively. The water depth is h. The hydrodynamic performance of the outer-floater can be evaluated by model tests in the wave tank with the consideration of the fluid viscosity.

3. Model design

3.1. Outer-floater

The outer-floater is made of the 6061 high tensile aluminum alloy. The thickness is 3.0 mm. The upper part is a vertical cylinder and the lower part is a conical bottom, which is designed to reduce the viscous dissipation. At the tip of the conical bottom, a steel ring is attached to link the mooring system. The detailed geometry parameters can be found in Fig. 2.

3.2. BI-PTO

This section describes the design and assembly of the BI-PTO mechanisms. There are three parts in the BI-PTO, i.e., the spring system, mass system, and damping system, among which the spring system is the most complex part to design, while the mass and damping systems are relatively easier.

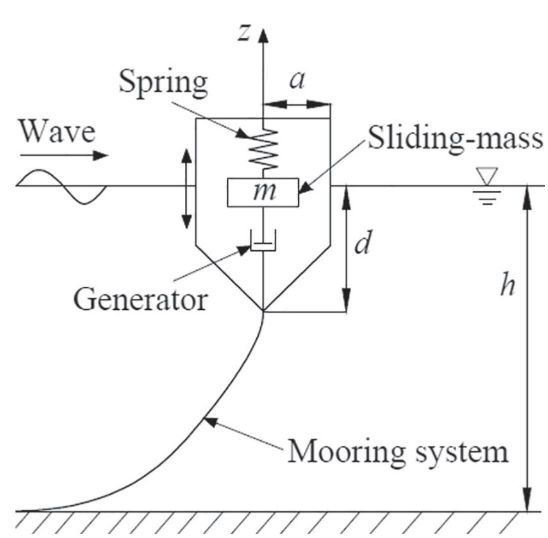

Fig. 1. The general schematics of the DR-WEC.