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Performance analysis of solo Duck wave energy converter arrays under motion constraints

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ABSTRACT

This paper studies the power capture performance of solo Duck wave energy converter (WEC) arrays. The barrier function method combined with a quasi-Newton BFGS optimization algorithm is applied to find the maximum captured power of the array when the Ducks are under motion constraints. Based on this optimized maximum captured power, the effects of separation distance, wave period, incident wave direction and Duck width on the array performance are investigated. For the two Ducks array, results show that the alternative constructive and destructive interaction stripes in the contour plot of the *q*-factor variation with non-dimensional separation distance are resulted from the diffracted wave pattern from each Duck, and the hydrodynamic interaction strength is reduced when constraints affect the performance. For the three Ducks array, the middle Duck shows larger variability of captured power than the side Ducks due to experiencing double in phase diffracted wave from the side ones. The captured power of the solo Duck WEC array is sensitive to incident wave direction, and arrays with Ducks of smaller width are found to have better performance in power capture efficiency.

1. Introduction

Wave energy conversion technology research has been ongoing since the 1970s as a response to the need of partly replacing fossil fuels with renewable energy sources. The Edinburgh Duck wave energy converter (WEC) was proposed at this time by Stephen Salter in the University of Edinburgh [1]. As one of the highly-efficient wave energy converters that have been proposed, the Duck WEC had been confirmed to reach more than 90% efficiency in 2D regular wave tests [2]. The cross section of a Duck is shown in Fig. 1a) [3]. The paunch part of this cross section is designed to strongly interact with the incident wave, while the stern part employs a circular shape so that its pitch motion causes no leeward wave [4], and the high efficiency of the WEC is resulted from this asymmetrical shape characteristic [5,6]. The original designed Duck WEC farm is constructed by the Duck WECs connected end to end along the rotation axis by jointed spines [4]. However, this scheme was canceled by the UK government in the 1980s due to high costs of the complex mechanical system and low reliability of the marine cables [2]. Soon after, the solo Duck WEC attracted more attention, since its efficiency can be further increased by the point absorber effect [3,7] and the mechanical system and mooring system are likely to be simpler. In Ref. [3], the hydrodynamic coefficients of a solo Duck were experimentally measured in a wide wave tank by applying a linear controller, and the point absorber effect of the solo Duck WEC was confirmed by a measured capture width as much as 1.6 times the Duck width in regular waves. Compared to the spine based Duck, the solo Duck needs to oscillate at larger amplitudes to capture maximum power due to its smaller width. In long waves, this may cause physical interference of motion excursion with the device limits and violation of the linear wave theory assumptions. In order to predict the maximum captured power of a solo Duck WEC within reasonable motion excursion range, Pizer numerically studied the solo Duck WEC performance under motion constraints by using a three-dimensional linear wave diffraction program, and showed

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that the solo Duck can achieve a maximum relative capture width over 2, despite the motion constraints [7]. Also, it has been revealed in Ref. [7] that performance of the solo Duck WEC decreases with more released degree-of-freedoms, which is also observed for its spine-based counterpart in Ref. [8]. Hence a solo Duck WEC favors a fixed pitching axis. Fig. 1b) shows a mooring configuration for a solo Duck with fixed pitching axis in head seas [9]. This taut mooring scheme resembles the "fixed-heave" mooring configuration proposed in Refs. [10,11] by removing the power take-off (PTO) devices from the tension legs. Provided that the pre-tension margin and stiffness of the tension legs are large enough, the pitching axis can be treated as fixed. Recently, Lucas et al. [12] and Cruz et al. [13] have applied the solo Duck device for desalination purpose, and an innovative circular cross section with an off-centered pitching axis is proposed to reduce manufacturing costs.

In order to apply the solo Duck WEC at a commercial level, a large number of the Duck WECs should be arranged to form a WEC array. The investigation of WEC array performance was initiated by Budal [14], who obtained the optimal captured power of a system with identical bodies oscillating in one or two modes based on the point-absorber approximation, which neglects the diffracted wave based on the assumption that the body dimension is much smaller than the wavelength [15], and it reveals that hydrodynamic interactions can cause both constructive and destructive effects of captured power. Since then, extensive work has been focusing on the hydrodynamic interactions among the devices in arrays for both axisymmetric geometries, such as semi-submerged spheres [15,16] and truncated vertical cylinders [17–19] and their combination [20], and angular dependent geometries, such as the thin ships [21] and rectangular barges [22], oscillating in either surge or heave mode. Kara et al. [19] predicted the hydrodynamic interactions in arrays with two and four truncated vertical cylinders in the time domain regarding both surge (described as sway in the original paper but at beam seas) and heave oscillating modes, and showed that more power is absorbed in surge mode than in heave mode at any separation distance and incident wave direction provided that the displacement in both sway and heave modes of the bodies in the array are identical, and that the surge mode shows a high performance at a wide frequency range while the heave mode is mainly concentrated at resonant frequency. Hence, different oscillating modes will cause different interaction characteristics. However, as far as the authors know, the hydrodynamic interactions of pitching devices, such as the solo Duck WEC, have received little attention. One analogous device is the oscillating wave surge converter (OWSC), which represents the Oyster device, as discussed in Refs. [23–26], showing that the captured power increases for both infinite and finite arrays of flap-type WECs resulting from the resonance of the system in the transverse mode and the devices in front of the cluster have an enhanced performance on average. However, we should notice that the OWSC is different from the solo Duck WEC not only in geometrical shape but also in the working water depth level (12 m for OWSC [27] and 60 m for the Duck WEC [28]).

The objective of this paper is to investigate the power capture performance of the solo Duck WEC arrays to benefit their application in practice. The solo Duck model is the same as that used in Refs. [7,28] and is shown in Fig. 1, and the pitching axis of each Duck in the arrays is fixed to retain high performance. The geometric description of the solo Duck and the arrays is introduced in section 2. As stated above, in order for the motion excursion be within a reasonable range, motion constraints should be applied. Thomas et al. [21] applied motion constraints to arrays with single and double rows of point absorbers, and shows that the captured power would be reduced when the ideal motion excursions exceed the limits. Different from the wave amplitude dependent motion constraints used in Ref. [21], which defines the excursion limits as two or three times the wave amplitude, in section 3, we introduce a fixed motion constraint regardless of wave amplitude. Then, a nonlinear constrained optimization problem is established to find the maximum captured power of the array and can be solved by combining the barrier function method with a quasi-Newton BFGS optimization algorithm. Before the optimization algorithm is realized, the hydrodynamic coefficients should be provided ahead. In section 4, we use a boundary element method (BEM) software to calculate the hydrodynamic coefficients, which are validated by comparing with measured results in the experiments of Ref. [3]. Finally, in section 5, based on the optimized maximum captured power, we presented and analyzed the performance of the solo Duck WEC arrays at different non-dimensional separation distances, wave periods, incident wave directions and Duck widths.

2. Geometry of the solo Duck and the arrays

The sketch of the solo Duck is shown in Fig. 1, where O is the pitching axis, R is the radius of the stern part; h_O is the depth of the pitching axis; W is the width of the Duck; h is the water depth; xyz is the global Cartesian coordinate system with y in the direction which the pitching axes of the Ducks should align to, z in the opposite direction of gravity acceleration and $z = 0$ representing the still water level. The dimension of the Duck is the same as that

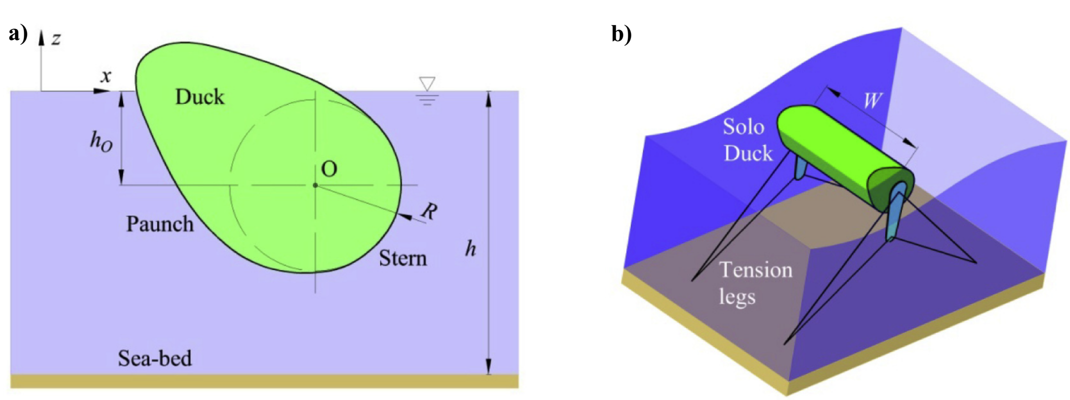

Fig. 1. Sketch of the solo Duck: a) a plane view of the cross section; b) isometric view of a taut mooring configuration for a solo Duck with fixed pitching axis in head seas.