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Experimental investigations on wave energy capture of two bottom-hinged-flap WECs operating in tandem

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ABSTRACT

This paper experimentally investigates the performances of two bottom-hinged-flap wave energy converters (BHF-WECs) operating in tandem. Firstly, the inertia effects of a single BHF-WEC operating in isolation are theoretically and experimentally examined to show their negligibility in coastal-water applications with the non-dimensional wave number ~ *O(1)*. Experiments of two in-tandem BHF-WECs with separation distance (*d*) varing from 0.5λ to λ (incident wavelength) with increment of *λ/16* are then conducted in a small wave basin. Hydraulic pumps are used as the power take-off and their forcing characteristics as an energy damper are determined using a rating platform. Time-series images of flapping motions of the BHF-WECs, recorded with high-speed cameras, are analyzed using a processing and analysis procedure based on the correlation algorithm to evaluate their capture factors (CF). The CF variations of the first BHF-WEC with *d* exhibit a sinusoidal wave form with wavelength of *λ/2*. The combined CF of the two in-tandem BHF-WECs is always greater than 1.0, indicating that the wave energy outside the frontal area is drawn via diffraction. It reaches the maximum at around *d = 14λ/16* with λ/4 apart from the minimum at around *d = 9λ/16* owing to the underlying mechanism of the Bragg Reflection.

1. Introduction

In coming decades, the world-wide concerns on global warming and expected peaks of reserves of conventional energy, such as petroleum, have resulted in wide and serious pursues of alternative energy solutions, especially the renewable energy. Marine energy, usually referred to as the combination of mainly wave energy, tidal energy, and ocean current energy, is quite promising in its tremendous potentials, renewability and zero-carbon emissions. Wave energy, being commonly regarded as the one with the largest potential one among marine energy resources (Ocean Energy Technology Overview, 2009), has particularly attracted many attentions and resulted in promoted developments of numerous types of wave energy converter (WEC).

So far, there have been hundreds of patents granted world-widely for WEC's designs and inventions, and related sub-system improvements (Trend Analysis on Technology Development of Ocean Wave Energy, 2009). Those proposed inventions can generally be classified into several categories based on the wave dynamic features and power take-off mechanism. Detailed reviews on device developments can be referred to, e.g., Falcão (2010). For the past decades, devices inspired by *the concepts of* oscillating water column, point absorbing and bottom-hinged pitching were mostly developed with different wave-device interaction characteristics. Among them, a bottom-hinged-flap WEC (BHF-WEC) oscillating in the wave surge direction (categorized as the Oscillating Wave Surge Converter, OWSC) has particularly in last decade been adopted (Folley et al., 2007a) and successfully resulted in designing and manufacturing several prototype WECs, e.g. Aquamarine Power Ltd's Oyster (Whittaker and Folley, 2012) and AW-Energy's WaveRoller (AW-Energy, 2012). The BHF-WEC concept has advantages such as quite efficient power conversion (Babarit, 2015), easy accessibility in nearshore waters (Folley et al., 2007b) and retract ability to submerge by folding the flap panel toward the sea bed to survive in the impact of extreme waves caused by extreme weather events, e.g. typhoons. In this regard, the BHF-WEC is quite ideal for harvesting wave energy in the typhoon-wave active near-shore waters around Taiwan. Therefore, the authors were initially motivated to theoretically and numerically study the performance of a single 2D BHF-WEC (Chang et al., 2015). We had preliminarily confirmed that the relations among the so-called mechanical impedances are the key factors to the energy capture (cf. Tom et al., 2017).

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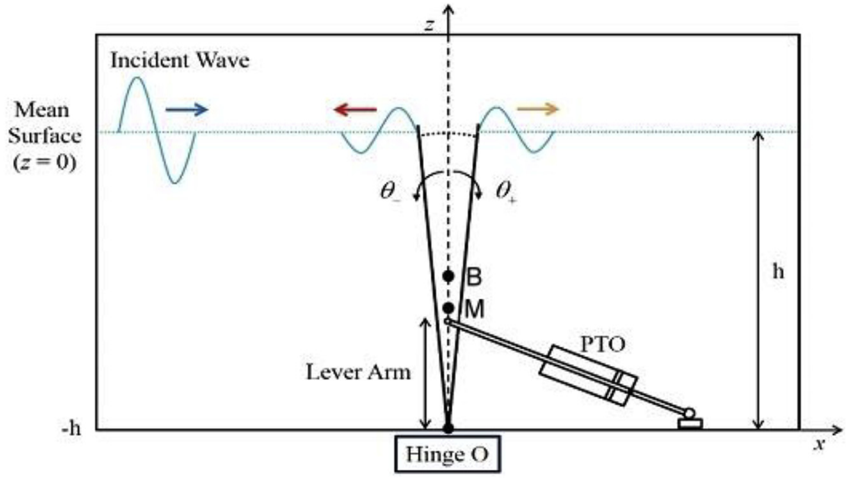

Fig. 1. Schematic of the 2D BHF-WEC problem.

Furthermore, multiple WECs forming a modular or array are considered to have potential in exploiting wave energy with higher efficiency (e.g. Wilkinson et al., 2017; Renzi and Dias, 2012a,b). Individual WECs in an array could interact with one another and thus behave differently than a single, isolated WEC does. As a result, this so-called "array interaction" has gradually become an important issue for wave energy exploitation. Budal (1977), Falnes (1980) and Evans (1980) were the pioneers in studying the array problem of the point-absorber type (e.g. buoy). For the array problem of BHF-WEC, Renzi and Dias (2012a,b) theoretically analyzed an in-line array configuration and found that high capture factors can be attained when the system is in resonance of transverse modes. In order to elucidate the interaction mechanism, two WECs in tandem operations as the simplest array form needs further studies. Srokosz and Evans (1979) extends Evans' theory (1976) to the case of two independently oscillating 2D cylinders in tandem. Theoretically, these two cylinders are capable of absorbing all the incident wave energy at a special condition away from their resonances, at which they can only absorb very little energy. Scher et al. (1983) and Wilke (1984) conducted a 2D model test in a wave flume with two in-tandem vertical panels oscillating in pure sway (linear) motions and compared the results with the theoretical predictions shown in Srokosz and Evans (1979). However, few attentions have been paid to the performances of two 3D BHF-WECs operating in tandem.

For WEC performance evaluations, numerical modellings have been generally acknowledged to be one of the powerful tools. Li and Yu (2012) had reviewed different numerical schemes for a single heaving device. Folley (2016) had further comprehensively reviewed the state-of-the-art numerical modeling for single devices of various concepts and arrays of heaving modes. Particularly on non-linear viscous damping, Yu and Li (2013) conducted successful RANS simulations for a two-body floating-point absorber wave energy system and showed significant influences on the performance of a WEC system. By incorporating the drag damping force term, Bhinder et al. (2015) compared the potential time domain viscous (PTDV) model with the CFD model with respect to a surging floating WEC and found a good agreement for regular wave conditions. So far, in-tandem bottom-hinged OWSCs and associated effects of non-linear viscous damping have not been reported possibly due to complicated interaction mechanism and computation. Thus, experimental studies with real fluids might help shed lights on critical issues to facilitate the developments of numerical modeling.

This paper first experimentally examines the inertial effects of the mechanical impedances on a single BHF-WEC, with a physical model having two hydraulic pumps as its PTO and a mechanism of tunable inertia. We especially focus on the impedances formed owing to the wave and the flap. This experiment is conducted with an image-based measurement with high-speed imaging, which is incorporated with the hydrodynamic theory for BHF-WEC developed by Chang et al. (2015) to form a robust experimental procedure. Then, another image-based methodology to evaluate the performance of wave energy capture (capture factor, CF) is developed with the same high-speed imaging. After that, we experimentally investigate the capture factors of two identical BHF-WEC models operating in tandem under a specific wave condition associated with the wave climates of Taiwan. As the separation distances between the two BHF-WECs varied from λ/2 to λ (incident wavelength) with increment of λ/16 and an additional test with a value slightly larger than λ, the corresponding oscillating motions of the BHF-WECs are measured using two high-speed cameras. The final results show the performance characteristics of BHF-WECs operating in tandem and an optimum separation distance in terms of λ.

2. Experimental setup and measurement technique

2.1. Theory of image-based measurement for BHF-WEC

The schematic of a 2D BHF-WEC interacting with incident waves with frequency σ and wave number k_i is shown in Fig. 1. And σ and k_i are related in the dispersion relation

$$\sigma^2 = gk_i \tanh(k_i h)$$

where h is the water depth and g the acceleration of gravity. The symbol $S(z)$ denotes the horizontal stroke of the flap's motion at z coordinates, and the flap pivots on O. In Fig. 1, $z = 0$ means the still water surface, and ρ is the water density. The damping coefficient of the PTO system is denoted as f_o, and L is the lever arm of the PTO's force. With Fig. 1, Chang et al. (2015) used formulations similar to the 2D linear wave-maker theory (Dean and Dalrymple, 1991) and obtained the relationship between the angular stroke θ_S and the incident wave height H as

$$\theta_S \sim \frac{H}{\sqrt{(W_1 + P_3)^2 + (W_2 + F_1 + F_2 + P_1 + P_2)^2}} \tag{1}$$

and the formula for the theoretical CF of BHF-WEC as

$$CF = \frac{E_{f_o}}{E_i} = \frac{2(W_1 \cdot P_3)}{(W_1 + P_3)^2 + (W_2 + F_1 + F_2 + P_1 + P_2)^2} \tag{2}$$

where E_{f_o} and E_i denote the energy taken off by the BHF-WEC's PTO and the incident wave energy in one wave period, respectively. In Eqs. (1) and (2), W_1 and W_2, F_1 and F_2, and P_1, P_2 and P_3 are the 2D, non-dimensional, mechanical impedances formed respectively because of the wave, the flap, and the PTO, as described below.

The impedance W_1 is formed owing to the waves radiated from the BHF-WEC and represents the effect of wave damping, i.e. radiation-