Experimental investigation on an energy-focusing type OWC wave energy converter array

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1. Introduction

Given its renewable nature and huge resources, wave energy harvesting has the potential to meet the power demand growth, and the goal of global energy transition [1]. However, this is still a challenging task as various types of wave energy converters (WECs) existing in public domain have equally shown to have a relatively low conversion efficiency and poor survivability in extreme sea conditions. In addition, the strategies for optimized array arrangement remain unclear due to the possible shielding effect among WECs. Subsequently, various techniques are proposed and investigated, including optimizations in either WEC geometries by reducing the energy loss [2] or array arrangement by incurring water resonances in a controlled manner [3].

DUT Offshore-Renewable-Energy (ORE) group has recently proposed a paradigm-changing technique, namely wave-energy-focusing, to improves the wave energy capturing [4-6]. Instead of reducing energy loss during the capturing as widely investigated, the technique introduces a carefully designed parabolic wall to increase the localized, capturable wave energy by reflecting incident waves from multiple directions to a certain location (referred as the focal point) and thus increasing the local energy by several times, i.e. the so-called wave-energy-focusing. It has been reported that the hydrodynamic efficiency of an oscillating water column (OWC) device arranged at the focal point is 6.5 times larger than that in open sea, and its wave-to-wire conversion efficiency is shown to be increased by 70% in scaled model testing.

As an extension, this work explores the possibility in arranging OWCs array according to the wave-energy-focusing introduced by the parabolic wall. Preliminary work suggests that there is more than one focal point within the local area, although the energy-focusing extent of each point is different. The focal points are then labelled according to its energy-focusing level. For example, the focal point that has the largest energy amplification is labelled as the primary one, that has the second large energy amplification is labelled as the secondary ones *etc.* A further optimization based on the aforementioned initial guess is also carried out, which further takes into account the complex wave-OWCs interactions. In addition, wave forces experienced by the primary OWC are analyzed and compared among OWC arrays to access if the device survivability can be improved by redistributing the extreme forces.

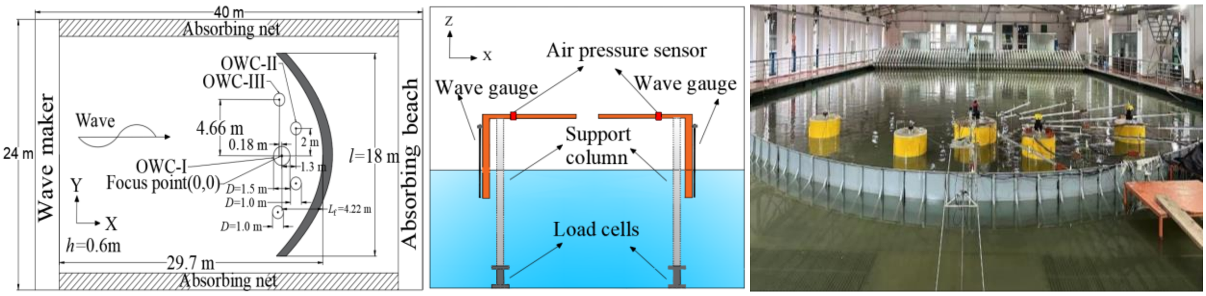
2. Experimental tests

2.1 Experiment setup

The experiments are conducted at a Froude scale of 1:15 in a wave basin at Dalian University of Technology, China. Here, the water depth $h = 0.6$ m. As shown in Fig. 1(a), a bottom-mounted parabolic wall composing of 11 steel plates was installed towards the end of the wave basin; each plate has a width of 2.0 m, a height of 1.0 m, and a thickness of 4.0 mm. The geometry shape of the parabolic wall is represented by $y^2=-4L_f x+(l/2)^2$, with the chord length of the wall l = 18 m and the theoretical focal distance $L_f = 4.22$ m.

It also can be seen in Fig. 1(a) that the array consists of five devices arranged in a W-shaped configuration. The positional relationships among the devices are also depicted in Fig. 1(a). The air chambers of the five OWCs were designed to be cylindrical, which are supposed to capture wave energy from all directions. The OWC chambers were made of perspex with a thickness of 10.0 mm. Each chamber was fixed by four small square support columns with a cross-sectional size of 5 cm × 5 cm, ensuring that the air chambers remained stationary during the experiment. The height and the draft of all air chambers are 0.6 m and 0.2 m, respectively. There is a circular orifice at the roof of each air chamber. The ratio of orifice area to the chamber roof area is 2.5%, as shown in Fig. 1(b). The Power Take-Off (PTO) system, which comprises a unidirectional impulse air turbine and a 75-W capacity permanent magnet synchronous generator, was attached to the orifice by a connecting flange. Additionally, two air pressure sensors were positioned on the roof of each chamber to monitor the pneumatic pressures within the chamber. For each device, four load sensors were used to connect the square support columns to the base of the water basin, facilitating the measurement of the loads exerted on the device. The OWC devices were symmetric about the central line of the parabolic wall, and thus forty-eight wave gauges were installed to measure the wave field in the right half of the domain, as shown in Fig. 1(c).

The optimized array arrangement of the five OWCs are achieved by the so-called real-time wave field reassessment based on a feed-forward process: (1) an OWC device that has an outer radius of 1. 5 m was arranged at the primary focal point, namely the primary OWC; (2) experiments (labeled as Case 1) for wave-primary OWC interactions were carried out and the corresponding local wave field was measured; (3) the secondary focal points (symmetric pair) were determined according to the wave field in (2), and two additional OWC devices that have a raddus of 1.0 m were installed at the secondary focal points, namely the secondary OWC devices. Thus, a 3-OWC-array was formed; (4) experiments (labeled as Case 2) for wave-3-OWC-array interactions were carried out and the corresponding local wave field was measured; (5) the tertiary focal points (also a symmetric pair) were then determined, and two additional OWC devices that had a radius of 1.0 m were installed, forming a 5-OWC-array; (5) experiments (labeled as Case 3) for wave-5-OWC-array were carried out. We note that smaller OWC devices were used at the secondary and tertiary focal points due to the fact that the energy focusing there are smaller.



(a) plane view of the OWC array (b) side view of the OWC device (c) arrangement of measuring instruments

Fig. 1 Schematic diagram of the experimental setup.

2.2 Wave-to-wire efficiency

The power output of each device $P_{ave,\,i}$ (i = 1, 2, 3 corresponding to the primary, secondary and tertiary OWCs, respectively) was measured by a power analyzer, which was connected to the PTO system by a three-phase rectifier bridge. The incident wave power for this device, denoted as $P_{In,\,i}$ is calculated by

$$P_{In,i} = P_{w,i} w_i, \tag{1}$$

in which w_i is the characteristic width of the device, and $P_{w,\,i}$ is the average energy flux per unit width of the incident wave calculated by

$$P_{w,i} = \frac{1}{2}\rho g A^2 C_g, \tag{2}$$

where g is gravitational acceleration; A is the incident wave amplitude and C_g is the group velocity of the incident wave. Then the wave-to-wire conversion efficiency of each OWC η_i, and the total conversion efficiency of the array η_{total}, are calculated by

$$\eta_i = \frac{P_{ave,\,i}}{P_{In,\,i}}, \quad \eta_{total} = \frac{\sum P_{ave,\,i}}{\sum P_{In,\,i}}. \quad (i=1,\ 2,\ 3) \tag{3}$$

in which the input and output power are double in Cases 2 and 3 due to symmetric pairs considered.

3. Results and discussions

Fig. 2 illustrates the temporal variations in the total power output for the three array arrangements with wave height of $H = 0.075$ m and wave period of $T = 1.8$ s. For Case 2 and Case 3, the total power output is obtained by adding the contribution from 3 or 5 devices. By introducing supplementary devices and arranging them strategically, the wave energy captured of the device array can be enhanced. Consequently, among the three cases, the wave energy capture is the largest in Case 3 as shown in Fig.2.

Fig. 3 shows the total conversion efficiency η from wave to wire for the three cases with $H = 0.075$ m. In Case 2 and Case 3, the increase in power output shown in Fig. 2 does not necessarily indicate an enhancement in the conversion efficiency. The constraints imposed by the energy focusing effect of the secondary and tertiary focal points limit the effective capture and conversion of the additional wave energy input facilitated by the parabolic wall. Consequently, the efficiency in Case 2 and Case 3 is lower than that observed in Case 1. Nevertheless, the conversion efficiency in all three cases can notably exceed the previously documented wave-to-wire conversion efficiency, including the 14% efficiency reported by Liu et al.[7] in laboratory experiments.

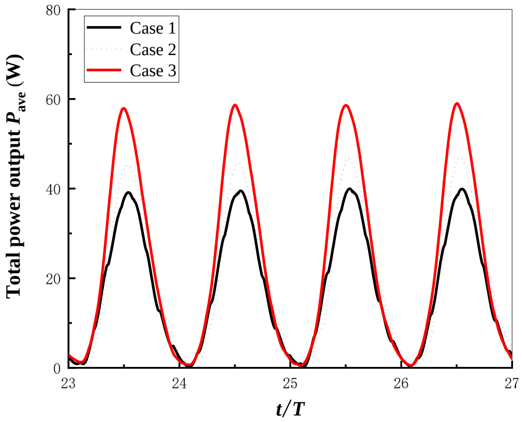


Fig. 2 The time histories of the total power output of the three cases for H=0.075 m, T=1.8 s.

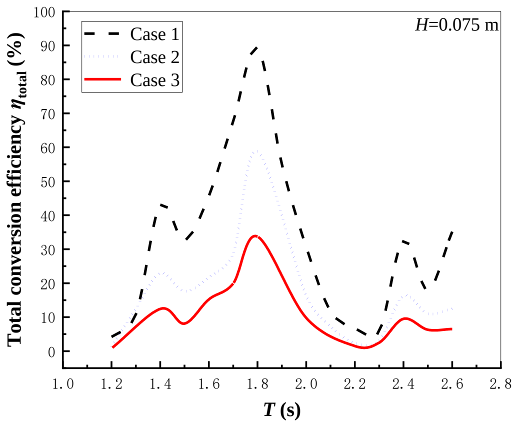


Fig. 3 The total conversion efficiency of the three cases with H=0.075.

The time histories of the horizontal wave forces on the primary OWC devices in three cases are presented in Fig. 4 with $H = 0.075$ m and $T = 1.8$ s. Positive and negative values here indicate that the wave forces are pointed towards downstream and upstream, respectively. As expected, for all the three cases investigated, the wave forces pointed towards upstream are larger than those pointed towards downstream. The former is associated with the action from (relatively smaller) incident waves and the latter the (relatively larger) reflected waves from the parabolic wall. Notably, the (negative) wave force is found to be the largest in the Case 1, followed by the Case 2 and Case 3. This suggests that the energy redistributing among OWC devices help to decrease the wave force on and thus increase the survivability of the primary OWC. Fig. 5 shows the comprehensively evaluation of the peak power output and wave force for the three cases. By arranging OWC in an array in a way informed by the energy-focusing would increases the total power output significantly by up to 52.6%, and reduced the wave force on the primary OWC by up to 66.7%. And the ability of this method for taking into account the wave energy capture and wave force distribution is proved.

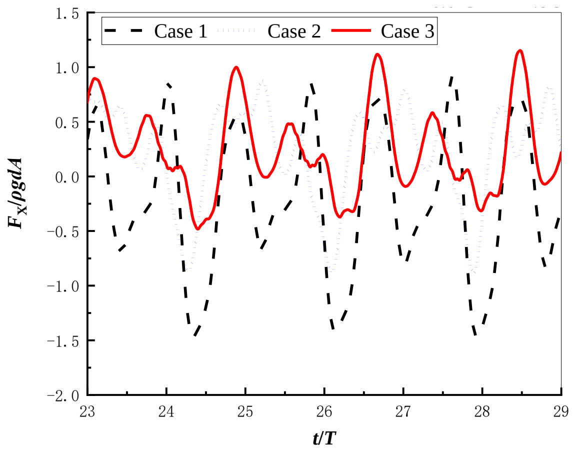


Fig. 4 Time histories of the horizontal wave force on the primary OWC device in three cases.

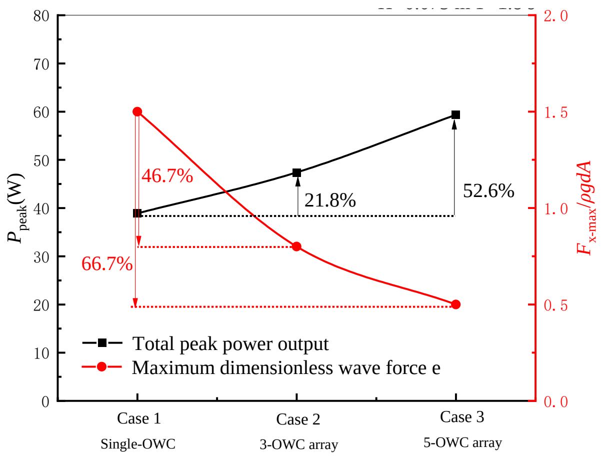


Fig. 5 The comprehensively evaluate of the performance of the three cases.

4. Conclusions

This study experimentally examined the energy capturing and the survivability of an energy-focusing type OWCs array. The findings indicate that it would increases the energy capture while ensuring the long-term survivability of the system. Further results will be presented at the workshop.

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