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Hydrodynamic interactions of oscillating wave surge converters in an array under random sea state

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ABSTRACT

The oscillating wave surge converter (OWSC) type devices (e.g., an Oyster wave energy converter) generate electric power via rotating motion about the bottom of the device. This type of wave energy converters have a wide power absorption bandwidth which enables the electricity generation at a wide range of wave frequencies. The power produced by the OWSCs could be maximised by configuring individual devices within an array. This paper examines the power production performance of multiple OWSCs in an array under regular, uni-directional irregular wave and multi-directional sea using the industry standard hydrodynamic software WAMIT. The performance of the OWSC array is represented as *q*-factor, which is a quantity defined as the ratio of the average total power produced in an array to the power produced by an individual OWSC. The results show that the OWSCs arranged in an array would produce both constructive and destructive interferences depending on the wave directions and frequencies. Further, the spreading function, the resonance bandwidth and the optimal spacing between the devices are shown to affect the performance of the OWSC significantly. The results provide an enhanced understanding of the behaviour and performance of the OWSCs when arranged in an array of different configurations.

1. Introduction

The Engineering and Physical Science Research Council (EPSRC) in the UK, supports marine energy research through funding grand challenge projects. The TeraWatt and EcoWatt2050 are the two projects funded by the research council, and the work presented in this paper forms part of project deliverables. One of the core objectives of these two project consortiums is provide the industry on the understanding to the limits of energy extraction by marine energy devices when deployed in array, and their impact on the nearshore and coastal environment as well as the marine ecology. The above projects have developed numerical models which will predict the environmental impact, if any, by deployment of wave and tidal energy converters in a very large scale array. The type of wave energy converters (WECs) considered for the present work is the oscillating wave surge converters (OWSC) as these devices possess relatively high capture width ratio of up to 60% (Babarit and Hals, 2011). The performance of the OWSC array subjected to different wave conditions is the subject of this paper.

As a means to reduce carbon emission from the burning of fossil fuel to generate energy, the electricity production from renewable energy has increased in popularity in the recent decades (International Energy Agency, 2014). In 2010, the world electricity production from renewable resources totals an amount of 4160 TWh. This is about 20% of the global electricity production of 21,500 TWh. Out of the total renewable energy production, less than 2% (60 TWh) was generated from waves and tidal resources (World Energy Council, 2013); and this quantity can be considerably increased by deploying large scale array of wave and tidal energy converters for successful technologies. While some of the individual device concepts are shown to perform well, deploying multiple devices in array would need careful planning for its successful long term operation in extremely complex sea environments. The multi-array arrangement could capture the wave energy effectively if the WECs are designed and arranged in its optimised configuration.

In order to assess the performance of the array, a parameter known as the interaction factor, also known as the *q*-factor (Budal, 1977), is commonly used to facilitate the discussions. Child and Venugopal (2010) have investigated the optimal configuration of point absorber type WEC array using the so called parabolic intersection and genetic algorithm methods by taking the *q*-factor as the objective function. They have shown that the optimised layout of the wave farms could be used to tune

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the performance of the WECs. The efficiency of the power absorption of multi-resonant oscillating water column devices has been investigated by Thiruvenkatasamy and Neelamani (1997) by experimental methods for various device spacings. Sarkar et al. (2014a) considered the wave effects of an oscillating wave surge converter and a heaving point absorber placed adjacent to each other. The findings reported in (Child and Venugopal, 2010; Thiruvenkatasamy and Neelamani, 1997; Sarkar et al., 2014a) confirmed that the hydrodynamic efficiency of the WECs increases when the array are spaced at their optimum spacing. Borgarino et al. (2012) investigated the wave interaction effects on the energy absorption in large array of generic wave energy converters and they claimed that the grouping of the WECs into array had a constructive effect when the damping of the power take-off is tuned properly and when the WECs have a large bandwidth.

A comprehensive work on the Oyster type OWSC was carried out in the Queen's University Belfast and University of Dublin (Renzi et al., 2014a; Whittaker and Folley, 2012) where they employed a semi-analytical solution to solve for the radiation and scattering problem. They confirmed that high levels of capture factor can be attained, even though the OWSC is not tuned to resonance with the incident wave field. Renzi et al. (2014b) have investigated the wave-power extraction from a single array of in-line Oyster OWSCs under regular waves by modifying the semi-analytical method; and they observed that the constructive interference is possible for certain period of the incident wave field and claimed that the array with the strongest constructive interaction is accompanied by the largest system efficiency. Renzi et al. (2014b) further reported that the energy extraction of a staggered array of Oyster OWSCs by using the modified semi-analytical and finite-element methods, and claimed that the finite element method (FEM) has advantages over the semi-analytical method due to its flexibility in reproducing virtually any array layouts, for arbitrary angle of incident of the incoming waves, and ensures an excellent reproduction of domains with complex geometries.

For the present work, the boundary element method (BEM) is utilised in assessing the performance of the OWSC array. Similar to the FEM, the BEM also enables the investigation of arbitrary array layouts for any incident wave angle and takes into account the full diffracting and scattering of waves. However, the computational time for the BEM could be greatly reduced when a large wave field is considered as only the boundary integral equation (BIE) of the submerged body wetted surface needs to be solved by employing the free surface Green's function (Newman, 1985). The utilisation of the BEM is well established in investigating the hydrodynamic interaction of multiple floating bodies as reported in (Williams and Abul-Azm, 1989; Wolgamot et al., 2012; Tay et al., 2009) and other non-OWSC type of WEC (Wolgamot et al., 2012; Delauré and Lewis, 2003; Vantorre et al., 2004; De Backer, 2009). For the first time in this paper, the BEM method is used to investigate the performance of the OWSC type WEC and the industry standard wave interaction analysis software WAMIT (Wamit Inc, 2011) has been selected as it has gained widespread recognition in the industry and research organisations i.e. project consortiums and EPSRC expert panels, for its ability to analyse complex structures with a high degree of accuracy and efficiency. Furthermore, the higher order boundary element method (HOBEM), an option available in WAMIT, is also employed to enhance the computational performance.

The OWSC device considered in the array is similar to that of the Oyster OWSC. As the present study considers a full scale array of OWSCs, there are some difficulties encountered in representing an Oyster type device with its PTO system, as the device information is commercially sensitive and it is not available in the public domain. Hence the results from WAMIT modelling is verified with their counterparts presented by Renzi and Dias (2013a). These verified hydrodynamic properties and PTO damping are given here for the benefit of other interested researchers in calibrating or verifying their hydrodynamic models. Together with the hydrodynamic properties, the pitch RAO and q-factor of the array under regular waves are also presented. In addition, we consider the effect of a more realistic sea by modelling the uni-directional irregular wave and multi-directional sea to study the device performance. A new set of results based on 12 OWSCs array arranged in a three-row configuration (known hereafter as the triple-array) is considered and the interaction factors (the q-factor) for the triple-array under regular and irregular waves are presented.

The authors were aware of the recently published papers by Sarkar et al. (2014b, 2016). and Noad and Porter (2015) which also investigated the performance of OWSC arrays. Although there are inevitable similarities between the present paper and the two above mentioned papers, the present paper aims in investigating the hydrodynamic interactions of multiple staggered arrays by taking into consideration the fully diffracted and radiated waves. The array layout investigated here is also based on a more realistic layout following the information given by the Scottish Government Agency – the Marine Alliance for Science and Technology for Scotland (MASTS) (O'Hara Murray, 2014). The hydrodynamic effects of the devices in each row towards another is being studied. As opposed to the semi-analytical method with a thin-rigid plate approximation used in (Sarkar et al., 2014b) and (Noad and Porter, 2015), the present paper takes into account the thickness of the OWSC which should not be neglected due to its significant effect towards the hydrodynamic performance of the device as proven in (Renzi and Dias, 2013b). The effect of directional spreading in the multi-directional sea is also taken into account in investigating the performance of the array. In addition to that, the influence of the resonance bandwidth towards the performance of the arrays is being investigated and the genetic algorithm optimisation scheme is being introduced to seek for the optimal spacing of the arrays. To the knowledge of the authors, these two areas of investigation on the OWSC type of wave energy device have not yet been published elsewhere in the literature.

The result presented here provide a greater understanding on the behaviour of large-scale array under the influence of a more realistic sea. It also offers a useful insight to the wave energy designers on ways to increase the energy efficiency by properly configuring the devices' spacing and resonance bandwidth. Last but not least, the optimal layout configuration of the array could be designed based on the understanding of the interaction behaviour of devices in the array. It must be noted here that the effect of viscous losses is being compromised in this paper due to the use of the linear potential theory that on the other hand allows the benefit of computational efficiency in running the hydrodynamic analysis of large-scale array in a multi-directional sea.

2. Problem definition

The triple-array oscillating wave surge converters considered for the hydrodynamic interaction study is shown in Fig. 1. Each OWSC comprises of the flap-type floating body (known hereafter as the flap) which is hinged at the bottom to a foundation, hence only allowing for the rotational motion about the hinge. The flap PTO system is modelled by a force represented by the damping coefficient B_{pto} to convert the kinetic energy into electricity. The flap has a width a, immersion depth d, thickness t and the hinge is located at a height c from the sea floor. The seabed is considered to be flat with a constant water depth of D. Waves approach the OWSC from an angle θ with a wave frequency ω. The OWSCs are then grouped into a three-row configuration where the first row comprises of five devices, second row four devices and third row three devices, thus a total of 12 OWSCs are placed in the wave farm. Each of the OWSC is separated by a distance s_p as shown in Fig. 1. The global X-Y coordinate system is located at the centre of the OWSC marked as $n = 3$ (see Fig. 1). The vertical coordinate, Z takes zero value at the free and undisturbed water surface. The local coordinate system (x,y,z) is at the hinge of each OWSC. The superscripts in s_p will be used in describing the optimisation process presented in Section 5.5.

The problem at hand is to determine the hydrodynamic interaction of the triple-array under the influence of regular, uni-directional irregular wave and multi-directional sea. Two wave spectra represented by the Pierson-Moskowitz (PM) and the JONSWAP formulations are considered