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Wave–structure interaction in hybrid wave farms

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HIGHLIGHTS

- We propose a hybrid wave farm with two types of Wave Energy Converters (WECs).
- The two types are: Oscillating Water Columns and Point Absorbers.
- We develop an analytical model of wave field–wave farm interaction.
- We validate the analytical model with numerical results, with excellent agreement.
- We perform a sensitivity analysis of wave direction and WEC spacing for two layouts.

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ABSTRACT

Hybrid wave farms, consisting of different types of Wave Energy Converters (WECs), have rarely been investigated so far. In this work we propose a hybrid wave farm consisting of Oscillating Water Columns (OWCs) and point-absorbers (PAs), and develop a semi-analytical model of the interaction between this hybrid wave farm and the incident wave field. The OWCs and PAs are modelled as truncated cylinders with and without moonpools, respectively, each with its own outer radius, inner radius, draft and mass. The hydrodynamic model solves the wave diffraction and radiation problems using linear potential flow theory and the methods of separation of variables and eigen-function matching. The independent oscillations of each WEC in any degree of freedom, including both translating and rotating modes, together with the pressure fluctuations of the air inside each OWC chamber, are all accounted for. The model is successfully validated based on numerical data, and thereupon applied to two configurations of the hybrid wave farm. We find that the excitation volume flux/forces are strongly dependent on the incident wave direction, the spacing between the WECs and, more generally, the configuration of the farm. The hydrodynamic coefficients, especially those of the PAs, are sensitive to the spacing and configuration. Notwithstanding the interest of these results in relation to the selection of the optimum configuration and WEC spacing of the hybrid wave farm for specific locations (with specific prevailing wave directions), the interest of this work lies in the semi-analytical model itself, which is found to be efficient in modelling the interaction of the hybrid wave farm and the wave field, and can be used in future wave farm projects.

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1. Introduction

Generated by wind, ocean waves may be regarded as a concentrated form of solar energy. The wave energy resource has been assessed in a number of areas, and the overall conclusion is that the resource is vast, but its spatial and temporal variability is considerable (e.g., Iuppa et al., 2015; López et al., 2015b; Carballo et al., 2015a,b; Khojasteh et al., 2018). The variability may be reduced for the sake of power production by combining wave energy with other renewables (Fusco et al., 2010; Astariz and Iglesias, 2016). In any case, harnessing wave power efficiently still represents a formidable technical challenge, which has inspired inventors and researchers since 1799 (e.g., Ross, 1995; Drew et al., 2009; Falcão, 2010; López et al., 2013; Zheng et al., 2015, 2016a,b; Zheng and Zhang, 2017a,b; Mustapa et al., 2017). This challenge is being tackled at present, with intensive technological developments under way.

The wave power that can be absorbed by a single Wave Energy Converter (WEC) is naturally limited. If wave energy is to provide a significant contribution to the energy mix, wave farms, i.e. arrays of WECs, must be deployed (Falcão, 2010). Unlike a single WEC working in isolation, the evaluation of the performance of a wave farm is all the more complex because of the hydrodynamic interaction between the WECs in the farm, which is significantly influenced by the dimensions and layout of the WECs, the incident wave direction and other parameters.

In this work a wave farm, consisting of different WECs (and hereafter referred to as a *hybrid wave farm)* is considered. More specifically, Oscillating Water Columns (OWCs) and point-absorbers (PAs) are considered. Both are at the forefront of the technological race in wave energy, and are the object of intensive R&D efforts (e.g., López and Iglesias, 2014; Sheng et al., 2014a,b, 2015; López et al., 2015a; Pereiras et al., 2015; Viviano et al., 2016; Flavià et al., 2017).

Analytical methods are generally efficient for providing a quick and accurate performance estimation of a wave farm consisting of WECs with simple geometries. Siddorn and Eatock Taylor (2008) gave the semi-analytical solution of wave diffraction and radiation from an array of floating cylinders with a view to an application in the field of wave energy, although neither motion nor power values were calculated. The following year, Garnaud and Mei (2009) presented an analytical study to evaluate power extraction by a compact array of small buoys, with spacings well below the typical wavelength. A circular array was found to be advantageous, with better efficiency over a broad range of frequencies than a single large buoy of equal volume. The semi-analytical method adopted by Siddorn and Eatock Taylor (2008) was later employed by Child and Venugopal (2010) to investigate the effects induced by the spatial configuration of an array of heave PAs, which are modelled by heaving truncated cylinders. More recently, a semi-analytical model for heaving PAs was also presented by Göteman (2017), whereas the PAs in this model can be either truncated cylinders or cylinders with moonpools. The results showed that the total power absorption could be improved if the wave farm consisted of devices of different dimensions. Apart from the study on an array of PAs, hydrodynamic analysis of an array of vertical axisymmetric OWCs, either restrained or freely floating, can also be carried out with semi-analytical method (Konispoliatis and Mavrakos, 2016). Theoretical analysis revealed the wave farm with restrained OWCs performed better in capturing wave power than that with floating OWCs. In addition to either OWCs or PAs, a farm consisting of a periodic array of large flap-type WECs was also analytically investigated by Renzi and Dias (2013a,b) and Sarkar et al. (2014a,b). Unlike a line of heaving buoys, an array of flap-type WECs was found to be capable of exploiting the resonance of the transverse modes, resulting in high capture factor levels (Renzi and Dias, 2013a). The analytical study of five layouts of 13 flap-type WECs revealed that a slightly staggered arrangement achieved better power extraction in random seas than an in-line arrangement (Sarkar et al., 2014a). Besides, Sarkar et al. (2014b) developed a mathematical model to address the problem of interaction between a flap-type WEC and a PA. Assuming a reasonably large distance of separation between the two WECs, the interaction between them by the evanescent modes of the disturbed potential were neglected.

Apart from analytical methods, various numerical simulations have also been widely used in the study of wave farms, especially when the WECs have complicated geometries. Babarit (2010) modelled wave farms composed of two either surging or heaving WECs using the Boundary Element Method (BEM). The alteration of the absorbed power due to wave interaction effects was found to decrease with the square root of the spacing between the WECs. Later, Göteman et al. (2014) studied different methods of reducing the power output fluctuations of a wave farm of PAs, which included varying: the number of PAs, the separating distance between units, the incoming wave direction, etc. The influence of the interactions between bodies on the overall annual energy production of larger wave farms (consisting of 9–25 PAs) was assessed by Borgarino et al. (2012), and the results showed that constructive and destructive interactions compensated each other over the range of wave conditions considered. Penalba et al. (2017) treated the hydrodynamic interactions as a function of the spacing between the WECs; for arrays with very small spacings, interactions were highly destructive. de Andres et al. (2014) employed a BEM-based model as well to analyse the influence of the array layout, WEC separation, number of WECs and wave directionality on the power absorption of wave farms composed of two-body heaving WECs. The BEM was also applied by Wu et al. (2017) to study the power capture performance of an array of solo Duck WECs. A better performance of this farm in capturing wave power was presented for the arrays with Duck WECs of smaller width. To investigate interaction of ocean waves with OWCs, Nader (2013) developed a fully numerical three dimensional (3D) finite-element model (FEM) in the framework of the inviscid potential flow theory. Although FEM is very limited in terms of computational domain size due to the computing resources required for the discretization of the entire water volume, it was deemed better suited to the consideration of internal air pressure effects of OWC and weakly non-linear effects. A FEM-based software was later used by Renzi et al. (2014) to investigate the dynamics of a wave farm made by flap-type WECs in the nearshore, showing that the excitation torque could be maximized when the incident wave acts simultaneously and non-symmetric layouts