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A numerical study on the hydrodynamic impact of device slenderness and array size in wave energy farms in realistic wave climates

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ABSTRACT

The future of wave energy converters lies in the design and realization of farms comprising of several devices, given the level of actual power flow for the individual devices and because of several operational issues. Therefore, not only the hydrodynamics of individual and isolated devices should be analysed, but interactions among devices within an array must also be carefully evaluated. In this paper, the authors attempt to parameterize the behaviour of small-, medium- and large-arrays of wave energy converters, in a particular staggered configuration, at four different locations characterized by realistic wave climates. The arrays studied in the present paper consist of heaving cylinders of different slenderness ratios. It turns out that for arrays of very short inter-device distances, regardless of the cylinder and array size, interactions are strong and lead to not negligible effects of destructive interference (total power reduction compared to the sum of isolated devices). Under these conditions, the bigger the array, the stronger the interactions and the higher the loss of power. However, a range of inter-device distances, referred to as intermediate region, where the power absorption is consistent and the interaction effect appears to be positive, has been found. This intermediate region is easily detectable for small arrays, but loses its ideal characteristics with the increase of the size of the array.

1. Introduction

Since the awareness of the exhaustion of traditional energy resources and the irreversible environmental impacts from fossil fuel combustion has increased, renewable and carbon-emission-free resources have been investigated intensively, with some resources already participating in the energy mix.

In this respect, wave energy may become an important renewable resource, as shown in Mork et al. (2010), if the existing technologies develop sufficiently. Many different concepts of wave energy converters (WECs), based on diverse working principles (e.g. heave point absorbers, oscillating wave sure converters or pitch attenuators) have been developed during the last decades, mainly focusing on individual devices. Heave point absorbers are floating bodies, whose horizontal extent is much smaller than a wavelength (Budar and Falnes, 1975). They absorb wave energy through their movement at the free-surface and the conversion into electrical power can be achieved through different power take-off (PTO) systems. In detail, the hydrodynamic analysis of single point absorbers is usually carried out using the well known boundary element method (BEM) theory, because of the wide availability of several commercial or open-source codes, such as WAMIT (WAMIT, 2013), AQWA (ANSYS, 2013) or NEMOH (NEMOH software, 2014), the relative ease of use and its appealing computational costs.

However, due to the actual power flow and high costs derived from construction, installation and maintenance of WECs, it seems that the only viable option is to incorporate more devices into ’wave farms’. It is therefore important to understand not only the behaviour of an isolated device, but also the interactions among the devices in a farm.

Hydrodynamic interactions in WEC arrays have been studied since the 1970's, when Budal introduced the concept of point absorber for array interactions and (Falnes, 1980) suggested an expression for the power absorbed by a WEC array. Different semi-analytical methods have been suggested to efficiently compute the hydrodynamic interactions within WEC arrays, such as the plain-wave method or the multiple scattering method introduced by McIver (1994) and Mavrakos and McIver (1998). Another alternative is the direct matrix method presented by Kagemoto and Yue (1986). All the aforementioned methods are based on the linear theory and provide exact solutions under certain assumptions.

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More recent works analyse such hydrodynamic interactions both numerically and experimentally: (Babarit, 2010) and (Göteman et al., 2014) analyse numerically the hydrodynamic interactions as a function of different inter-device distances for different array configurations, including very large separating distances of over 2000 m, while (Stratigaki et al., 2014) investigates experimentally the interactions in large arrays. Some effort has also been dedicated in methods for array layout optimisation, for example (Child, 2011) or (Child and Venugopal, 2010), which consider wave directionality and array layout, or a more recent study (Ruiz et al., 2015), based on the hydrodynamic model recently presented by McNatt and Venugopal (2015), considering six different parameters to optimise the layout. De Chowdhury et al., presents an overview of the different methods to analyse WEC arrays and a whole section is given to WEC array modelling techniques in Folley (2016).

So far, most of the work for the analysis of the interaction among devices in a wave energy array has been carried out under regular wave conditions. Nevertheless, a more detailed approach is needed in order to accurately study the hydrodynamic interactions. For this reason, there is a gradual move in the literature towards studying such interactions in spectral seas: (Ricci et al., 2007) studies cylindrical heaving bodies of different geometries in two different array configurations at the Portuguese western coast, Folley and Whittaker (2009) analyses absorbed power and the optimal layout including sub-optimal control in WEC arrays at the European Marine Energy Centre (EMEC), comparing results to those obtained under regular waves, and (Borgarino et al., 2012) studies several different configurations using the scatter-diagram information at Yeu Island in France.

The size of arrays may also be important, so large arrays have been studied in some works in the literature, such as, Tissandier et al. (2008) which studies 18 *SEAREV* devices in the array, Singh and Babarit (2014) which studies 25 cylinders and 25 surging barges or (Engström et al., 2013) which studies 32 *AWS* devices.

(De Andrés et al., 2014) presents different factors that influence the behaviour of wave energy devices in an array, including the array configuration, the inter-device distance, the number of devices in the array and the incident direction of the wave. However, arrays of only 2–4 WECs are investigated, which may lead to incomplete and/or misleading conclusions. In addition, the geometry of the devices, particularly the slenderness ratio (radius/draft) in axisymmetric devices as shown in Ricci et al. (2007), and characteristics of the incoming waves may also influence the behaviour of the WECs in the array.

In this paper, the influence of the slenderness and the number of devices in a wave farm on the hydrodynamic performances is evaluated numerically in realistic wave climates, as function of inter-device distance. Scatter diagrams of four different locations, representative of various resource distributions, have been used in the analysis.

Section 2 introduces the hydrodynamic model used in the simulations, Section 3 describes different device geometries, the array layout configuration, array sizes and the locations, while Section 4 shows the results for each case. Finally, conclusions are drawn in Section 5.

2. Hydrodynamic model

The interaction between wave absorbers and fluid has very often been modelled by means of the linear diffraction theory, under the assumption of inviscid fluid and incompressible irrotational flow. In this study, linear theory has been considered, assuming wave and body motion amplitudes to be small with respect to the wavelength, and allowing the formulation of the solution of the boundary conditions and Bernoullis equation in terms of velocity potential and free surface displacement. The influence of nonlinear hydrostatics and Froude-Krylov forces for assessing the absorption of wave energy is still under investigation in order to define appropriate ranges of validity even if evidence of their influence on dynamics of bodies is well-known (Wolgamot and Fitzgerald, 2015; Penalba et al., 2017). Nevertheless, the same authors suggest that the linearization of the free surface condition is consistent with the basic definition of point absorber (main dimension much smaller than the wavelength), and of course the effects are increasing with the wave amplitudes. Similarly, nonlinear radiation effects seem to be not so relevant. For all these reasons (small size of the device, small amplitudes, minor effects of nonlinear radiation), the linear theory seems to be a good choice for identifying the main characteristics of the interactions among devices, without no major impact on accuracy.

According to (Chakrabarti, 2005), indeed, when the bodies are large enough, the flow remains attached to the surface, and therefore, the resulting force on the body can be performed by integration of the pressures. In such cases, Froude-Krylov forces and diffraction and radiation forces can be used for the estimation of forces. When not applicable, other models for the fluid structure interactions should be used, in order to include viscous effects (for example, Morison equation, including viscous drag force, as an inertial term) or proceed to solve full Navier Stokes equations by means of Computational Fluid Dynamics (CFD), which will make the problem very cumbersome from the computational point of view.

In particular, the diffraction model can be applied either when the dimensionless Keulegan-Carpenter (KC) number is lower than a threshold value, with this threshold generally set to the value of 6, or -following an entirely equivalent interpretation- when the diffraction parameter $\pi\frac{D}{L}$ is greater than 0.5, where D is the significant dimension for the body (i.e. the diameter for a vertical cylinder) and L is the wavelength. Essentially, following Chakrabarti (2005), from mild to moderate sea states the linear diffraction model can be applied. Even in extreme sea states, viscous drag forces are negligible when the ratio $\frac{H}{D}$ is lower than 2. Therefore, for the case studies in the present paper, the drag effect is almost negligible, and only the inertial term could be taken into account for the estimation of forces, even when the Morison equation should be used.

All the above considerations yield to the conclusion that diffraction forces cover all the major effects on forces, given the occurrence matrices and scatter diagrams in Fig. 4.

Hydrodynamic coefficients are in this case obtained by using the commercial code AQWA (ANSYS, 2013). Mesh density for the simulations has been decided after a mesh convergence study for an isolated device, where the best compromise between accuracy and computational costs was found to occur using a mesh of 2016 nodes and 504 panels. The same number of nodes and panels is used for all simulations. In such simulations, a range of 50 frequencies between 0.03 and 2 rad/s was analysed, which covers the vast majority of the exploitable ocean waves.

In the case studies, waves are modelled as 2D long-crested cylindrical waves, i.e. a unidirectional spectrum without any spreading factor is used in all the simulations, and the incoming waves are always perpendicular to the main direction of array. In undisturbed field, in general, the effects of directional spreading becomes particularly relevant in case of nonlinear waves and shallow water (see Arena et al., 2008). As a matter of fact, the hydrodynamic performance of the array should depend on the incident wave direction and taking into account a directional spreading function may reduce the final power output of the array especially if the devices are aligned with the mean wave direction, as noticed by Ricci et al. (2007). However, given the configuration of the layout of devices studied in this work and the linearity of the wave model adopted, it is reasonable to consider those effects to be of smaller entity and they have been not taken into account within the scope of this work.

2.1. Single-device

Once hydrodynamic coefficients are calculated, the equation of