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On the numerical modeling and optimization of a bottom-referenced heave-buoy array of wave energy converters

F. Fàbregas Flavià *, A. Babarit, A.H. Clément

Ecole Centrale de Nantes, LHEEA, UMR CNRS 6598, Nantes, France

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ABSTRACT

Compact arrays of small wave absorbers have been proposed as an advantageous solution for the extraction of wave energy when compared to a big isolated point absorber. Numerous challenges are associated with the numerical modeling of such devices, notably the computation of the hydrodynamic interactions among the large number of floats of which they are composed. Efficient calculation of the first-order linear hydrodynamic coefficients requires dedicated numerical tools, as their direct computation using standard boundary element method (BEM) solvers is precluded. In this paper, the Direct Matrix Method interaction theory by Kagemoto and Yue (1986) is used as an acceleration technique to evaluate the performance of a generic wave energy converter (WEC) inspired by the Wavestar *SC-concept* and to perform layout optimization. We show that there exists an optimum number of floats for a given device footprint. Exceeding this number results in a "saturation" of the power increase, which is undesirable for the economic viability of the device. As in previous studies on multiple absorber WECs, significant differences were observed in energy production among floats, due to hydrodynamic interactions.

1. Introduction

A great variety of technologies to extract power from ocean waves have been proposed, some of which are currently under development. These wave energy converters (WECs) may be classified by several methods [6], for example on the basis of size: devices whose characteristic length is much smaller than the wave-length of the incoming waves are referred to as point absorbers, and have been the object of numerous studies. Their responses are characterized by a resonant peak over a narrow band of frequencies of the incident wave spectra, and control strategies may be applied to increase their energy absorption [7].

Another category, often referred to as multi-body WECs, consists of a group of multiple closely-spaced point absorbers attached to a common fixed or floating support structure. Within this category, several configurations have been proposed, including the FO^3 platform [16], the Manchester Bobber [17] and the Wavestar [9]. The former two consist of a square lattice of floats linked to a common supporting structure through a Power Take-Off (PTO) system. In contrast, floats in the latter are distributed with a linear arrangement and connected to both sides of a fixed bridge structure through rigid arms.

Inspired by the FO^3 device, Garnaud and Mei [8] analyzed the performance of compact square and circular arrays of cylindrical point absorbers and compared them to a bigger float having an equivalent displacement. They found that, unlike the

* Corresponding author.
E-mail address: francesc.fabregas-flavia@ec-nantes.fr (F. Fàbregas Flavià).

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large buoy, the circular array of multiple point absorbers had good efficiency over a broad range of frequencies. They made use of the method of homogenization, which offers great savings in computational time, and is valid when both the device size and the separating distance between units is small in comparison to the incident wave length.

A different acceleration technique, a mode expansion method [14], was used by Taghipour and Moan [16] to study the FO^3 device. They evaluated both the response of the floating rig supporting 21 floats and the wave energy absorption capabilities of the WEC. For this particular configuration, they found that the power produced was independent of the mean wave direction for short-crested ocean waves. In addition, they observed significant differences in power production between floats.

A comparison of two FO^3-type WECs, one with 21 aligned buoys and the other with a staggered grid configuration of twelve buoys, was performed by De Backer et al. [4]. Calculations were undertaken in the frequency domain and the hydrodynamic coefficients were calculated using the Boundary Element Method (BEM) code WAMIT. They observed that the 21-unit configuration was able to produce only 25% more power than the 12-unit configuration. A similar result was observed in experiments carried out by Garnaud and Mei [8] in which an increase in the density of floats for tight configurations led to a relatively small increase in capture width. The work of De Backer et al. [4] addressed the impact of constraints and several PTO optimization strategies. It was found that the former reduced the power production of the arrays whereas the application of individual optimization led to a significant increase in energy capture when compared to other less sophisticated strategies. The same conclusion was reached by Nambiar et al. [13] after a study of three buoys of the Wavestar prototype that compared different types of resistive and reactive PTO control strategies using a dedicated time domain model including PTO damping force constraints.

Different versions of the Wavestar multi-body WEC device have been presented in Hansen et al. [10]. In the present paper, as we wish to illustrate the interest of the Direct Matrix Method when dealing with large groups of floating bodies, we choose the 60-float *SC-concept* as a working example. The objectives are i) to examine the power capture of a generic bottom-referenced heave-buoy array (BR-HBA) inspired by this WEC, and ii) to conduct an optimization of both its layout and the size of the floats.

The study is carried out in the frequency domain using linear potential flow theory. No constraints nor sophisticated Power Take-Off tuning strategies have been considered herein and, as in De Backer et al. [4], the effect of diffracted waves from the supporting piles of the structure has not been addressed. Therefore, results should be regarded as preliminary estimates of the power generation potential of this type of technology.

In the following sections, a detailed description of the system is provided and the numerical modeling in the frequency domain is detailed, with particular emphasis on the procedure used for efficient computation of the hydrodynamic coefficients of the floats in the array. Some results are then presented, detailing the response of both an individual and a small cluster of three floats. Following the analysis of individual units, relevant layout configurations derived from optimization studies on the reference 60-unit configuration are analyzed in detail. Finally, results concerning the impact of float size on power capture are presented.

2. Methodology

2.1. Description of the System

The bottom-referenced heave-buoy array WEC studied herein is composed of 60 hemispherical floats regularly distributed along both sides of each of the three arms of a fixed bridge structure (see Fig. 1). Each individual float is rigidly connected to an arm mounted on the supporting frame by means of a hinge joint. In our modeling, the hydraulic Power Take-Off (PTO), which transforms the rotation into electrical power in the real device, is replaced by a basic linear damper.

A global Cartesian reference system (X, Y, Z) is used to define the ambient incident wave propagation angle (β) with respect to the multi-body WEC. In addition, a local Cartesian reference system (x, y, z) centered at each float is used to redefine the incident wave angle with respect to each individual unit. Fig. 1 shows a schematic of the system, and the main parameters are specified in Table 1.

2.2. Equation of motion

The linear first-order equation of motion of a single hemispherical point absorber float can be written as:

$$(J + A)\ddot{\gamma} + (B + B_{pto})\dot{\gamma} + K^h\gamma = M^{ex} \tag{1}$$

where γ is the angle of rotation along the bearing axis, J the inertia of the float, A and B the radiation hydrodynamic coefficients of added-inertia and damping moment respectively, B_{pto} the damping moment of the PTO system, K^h the hydrostatic stiffness and M^{ex} the excitation moment.

Assuming that the rigid arm connecting the float to the bearing is weightless, the hydrostatic stiffness coefficient K^h expressed with respect to the axis of rotation can be computed as in Babarit et al. [2]:

$$K^h = K_B^{h,roll} + \rho g V(z_B - z_A) - mg(z_G - z_A) + K_B^{h,heave}(y_B - y_A)^2 \tag{2}$$