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Factors that influence array layout on wave energy farms

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ABSTRACT

This paper presents a study of the factors that influence array layout on wave energy farms. The WEC considered is a two-body heave converter extracted from Babarit et al. (2012). Simulations were run through a time domain model from de Andres et al. (2013) with irregular waves considering different sea states. Factors analyzed in this paper are array layout, WEC separation, number of WECs and wave directionality. Results show that wave directionality is very important in order to achieve constructive interference. When looking at the number of WECs the conclusion is that as the larger the number of WECs, more interactions are possible and therefore, the higher the interaction factor is. Regarding array layout, triangle and square configurations were found to be similar and the efficiency of each one depends on the most probable peak period. Separating distance was found to be a key factor and $L_{10}/2$ was set as the optimal one. Finally, wave climate was classified in different subtypes around the globe. The optimum layout in these sites was assessed. The influence of directionality was studied and the triangular configuration was found to be the most favorable for multidirectional climates while square configurations were most adequate in unidirectional climates.

1. Introduction

Wave energy is currently at prototype testing stage. The most advanced prototypes are under real sea testing conditions and single units have been already deployed. Nevertheless, in the future, in order to reduce cost and achieve a better performance Wave Energy Converters (WECs) have to be deployed in the sea in the form of large arrays. These devices in arrays experience forces due to waves scattered and radiated from other devices, impacting on the power production of the WECs and sometimes these forces influence the array total production achieving a power gain with respect to the individual production (Walker and Taylor, 2005). These factors have proven to be the key in carrying out research in this field, so as to maximize production.

The interaction between radiated and diffracted waves can be constructive (summing amplitudes) or destructive (subtracting amplitudes). The interaction between WECs has been measured based on the interaction factor (or gain factor) q that is defined as the ratio between the output power of the array of N devices divided by the output power of an individual device multiplied by the number of devices. When the interference is constructive $q>1$ and when is destructive $q<1$.

The first study on WEC interactions corresponds to Budal (1977) where he introduced the concept of point absorber for array interaction taking into account that the scattered waves can be neglected and only radiated waves are essential for the analysis. Subsequent studies carried out by Falnes (1980) and Falnes and Budal (1982) affirmed that the *q factor* can be higher or lower than 1 depending on the wave period and the array configuration. The most recent studies correspond to Garnaud and Mei (2009) who investigated a set of equations for dense arrays of heaving WECs. Child and Venugopal (2010) and Child (2011) show two different methods for array optimization (genetic algorithm and parabolic intersection methods) that were implemented considering wave directionality and array layout for generic point absorber. Some of the latest studies carried out on array configuration correspond to Babarit (2010) and Borgarino et al. (2012). Babarit (2010) demonstrated that in general, the q factor is variable in regular waves with respect to the period of incident waves, however in irregular waves the q factor is less dependent on wave period. They also studied the influence of long separating distances on a generic wave energy array and demonstrated that wake interactions are negligible for separating distances over 2000 m. Finally Borgarino et al. (2012) studied several configurations of wave energy arrays reaching the conclusion that in general, and considering a generic point absorber oscillating in heave or surge, triangle based arrays are the best configuration because they allow reaching optimum masking effects (destructive interaction). Wolgamot et al. (2012) studied the impact of directionality of regular waves over an array of heaving cylinders reaching the conclusion that

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wave direction is an important parameter in order to orient wave energy farms and achieve a maximum in production.

Nowadays, wave energy arrays have been studied under regular waves and with frequency domain models, however a more realistic approach is needed. Therefore, the objective of this paper is to assess the different factors that influence wave energy array behavior under a time domain model with irregular waves in order to find the optimum one. The factors included in this study will be array configuration, separating distance, number of wave energy converters and wave directionality. Finally a new analysis will be performed taking into account the marine climate variability around the globe. Climates will be classified taking into account H_s, T_p and variance in wave directionality and then optimum array configurations will be discussed for each type of marine climate. Also optimum locations for these types of WECs are discussed.

2. Numerical model description

The model simulated numerically in this paper is shown in Fig. 1 and described in paragraph 3. The numerical model used in this paper is explained in detail in de Andres et al. (2013).

The system of equations based on Cummins equations for a two-body heave converter is presented in the following equations:

$$(m_1+A_{\infty_1})\ddot{z_1}(t)-A_{\infty_{12}}\ddot{z_2}(t)=F_{excitation_1}(t)-Gz_1-C_{PTO}[\dot{z_1}(t)-\dot{z_2}(t)] - \int_0^t K_1(t-\tau)\dot{z_1}(\tau)\,d\tau - \int_0^t K_{12}(t-\tau)\dot{z_2}(\tau)\,d\tau - F_{vis_1}(t) \quad (1)$$

$$(m_2+A_{\infty_2})\ddot{z_2}(t)-A_{\infty_{21}}\ddot{z_1}(t)=F_{excitation_2}(t)-Gz_2+C_{PTO}[\dot{z_2}(t)-\dot{z_1}(t)] - \int_0^t K_2(t-\tau)\dot{z_2}(\tau)\,d\tau - \int_0^t K_{21}(t-\tau)\dot{z_1}(\tau)\,d\tau - F_{vis_2}(t) \quad (2)$$

where

- m_i is the mass of the object considered,
- A_{∞_i} is the infinite added mass of the object considered (at infinite frequency),
- $z_i(t)$ is the vertical displacement of the body (z origin at the Still Body Level, SBL) and the dots mean the order of time derivation,
- $F_{excitation_i}$ is the excitation force,
- G is the hydrostatic stiffness of the object considered,
- C_{PTO} is Power Take Off damping Constant,
- $\int_0^t K_i(t-\tau)\dot{z}_i(\tau)\,d\tau$ represents the convolution integral where $K(t)$ represents the fluid memory effects,
- F_{vis_i} represents the viscous force.

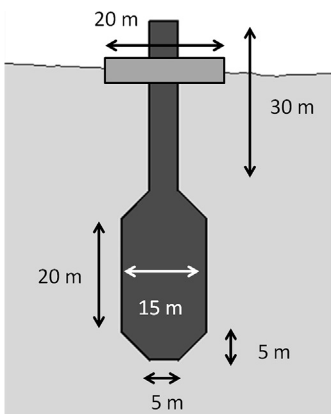

Fig. 1. The two bodies heave converter analyzed.

This model is based on the Cummins equation (Cummins, 1962) for a two-body system. The most challenging task in Cummins equations is to efficiently solve the convolution integral. This integral is not convenient for the analysis of motion of WEC systems. In order to avoid this problem, one of the methods proposed in the literature is to approximate the convolution integral by using a state-space system (Yu and Falnes, 1995). Taghipour et al. (2008) show that solving the convolution integral is approximately 8 times slower than using state-space realizations.The problem therefore switched from solving the convolution integral to finding the elements of the state-space system which approximates that convolution integral. This state-space receives as input the velocity of the body and produces an approximation to the convolution integral as an output. Several approaches have been used in the literature, for example Yu and Falnes (1995), Duclos et al. (2001), Kristiansen et al. (2005) and McCabe et al. (2005).

A description of the different methods can be found in Taghipour et al. (2008). These techniques share a starting point, as all of them require the use of information taken from a 3D Boundary Element Method (BEM) such as WAMIT/WADAM.

A general state-space has the form

$$\dot{\mathbf{X}}(t)=A\mathbf{X}(t)+\mathbf{B}u(t)$$
$$y(t)=\mathbf{CX}(t) \quad (3)$$

where $u(t)$ and $y(t)$ are called input and output respectively of the state space and $\mathbf{X}(t)$ is the state-space vector. Each convolution integral in Eqs. (1) and (2) is approximated by a state-space:

$$I_{ij}(t)=\int_0^t K_{ij}(t-\tau)\dot{z}_j(t)\approx \left| \begin{array}{l} \dot{\mathbf{X}}_{ij}(t)=A_{ij}\mathbf{X}_{ij}(t)+\mathbf{B}_{ij}\dot{z}_j(t) \\ I_{ij}(t)\approx y(t)=\mathbf{C}_{ij}\mathbf{X}_{ij}(t) \end{array}\right., \quad i=1,\ 2 \text{ and } j=1,\ 2, \quad (4)$$

where $\mathbf{X}_{ij}(t)$ is the state-space vector and $\dot{z}_j(t)$ is the input of the system.

Following Taghipour and Perez (2008), once the coefficients for the previously mentioned state space system are obtained using WADAM and the identification technique of Perez and Fossen (2009) a global state-space is built and the free dynamics of the 2 body WEC can be described by a global state-space representation. Using this global state-space approach, the whole Cummins equation can be replaced by Eq. (4).

$$\left| \begin{array}{l} \dot{\mathbf{X}}(t)=A\mathbf{X}(t)+\mathbf{B}F_{excitation}(t) \\ y(t)=\mathbf{CX}(t) \end{array}\right. \quad (5)$$

where the input of the state-space is the excitation force, $F_{excitation}(t)$, the output is the state-space vector $X(t)$ that comprises the four state-space vectors of the convolutions, the displacement and the velocity vectors. The whole substitution and construction of the system is explained and validated in de Andres et al. (2013).

The results of this system are the displacements and velocity of the two bodies through time.

3. Simulations

The study of factors that influence WECs array is carried out for the converter described in Fig. 1. This WEC is a heave converter extracted from Babarit et al. (2012) and studied also in de Andres et al. (2013), which is a generic two body point absorber consisting of two objects: a buoy (1), that is only partially submerged and a float (2) that floats on the top of surface. Both objects are only allowed to move in heave and the union between the bodies is made through a linear PTO connection. In this case energy is extracted from the relative motion between the float and the buoy. The instantaneous power captured by the device is obtained using expression (6) assuming power production to be proportional to