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Impact of long separating distances on the energy production of two interacting wave energy converters

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ABSTRACT

In this paper, wave farms composed of two either surging or heaving wave energy converters are considered. Using a numerical model which takes into account wave interactions, the impact on the absorbed wave power of the separating distance between the two systems and the wave direction is studied. In regular waves, a modified q_{mod} factor is introduced and it is found to be more relevant than the usual q factor for identifying this impact. Then, it is shown that, asymptotically, the alteration of the energy absorption due to wave interaction effects decreases with the square root of the distance. This is a slow decay, which leads to a still significant modification of the wave energy absorption at long distance (up to 15% at a distance of 2000 m). In irregular waves, it is shown that constructive and destructive effects compensate each other, particularly when considering the mean annual power. It leads to a smaller impact of the wave interactions on the absorbed energy and shorter distances (smaller than 10% for distances greater than 400 m). Finally, conclusions on if wave interactions should be taken into account or not when designing a wave farm are drawn in function of the distance.

0. Introduction

Wave energy converters (WECs) are designed to be deployed in large arrays composed of many systems. In such arrays, each single system interacts with all the others by absorbing, radiating and diffracting waves. These wave interactions have an impact on the energy output from arrays, which motivated many research studies over the last decades.

The effect of array interactions on the energy production is usually quantified by the q factor, defined as the ratio between the output power from an array of N systems divided by N times the output power from a single isolated system. If $q<1$, it means that the averaged energy production of each system in the array is lower than the energy production of isolated systems. Hence, the wave interferences have a destructive effect on the output power of the wave farm. Reversely, if $q>1$, the effect is constructive.

In the pioneering work of Budal (1977), Evans (1979) and Falnes (1980), it has been shown that the q factor can be either higher or lower than 1 depending on the wave frequencies and the array layout. This means that it can exist farm arrangements in which the energy production from a sum of WECs is more than the sum of the energy production of each single WEC. However, in Thomas and Evans (1981), it is stated that farm layouts should be designed in order to minimise destructive interferences for practical applications. Since then, many studies have been conducted by various authors on linear arrays of small devices (Simon, 1982; McIver and Evans, 1984; Mavrakos and McIver, 1997; Falcão, 2002; Justino and Clément, 2003; Child and Venugopal, 2007; Cruz et al., 2009; Weller et al., 2009).

In most of these studies, only closely spaced arrays are considered. In such arrays, wave interactions are strong because each WEC feels the wave perturbation coming from one or several others WECs in the array. It is well known (Falnes, 2002) that the wave perturbation is composed of a near field part which decays with the inverse distance to the body which generated it; and a far field part which decays with the square-root of that distance. Hence, when the distance between the WECs in the array is sufficiently large, wave interactions become negligible.

For practical reasons (moorings for example), arrays of WECs can become sparse, with typical separating distances of a few hundred meters. Taking into account the considerations of previous paragraph, one could ask if the WECs are far enough in order to neglect the wave interactions. This is the question addressed in this study by considering two arrays of two generic wave energy converters—one heaving and one surging device—located at several different distances one from the other.

In the first part of this paper, a numerical model of the array is derived in the frequency domain. In the second part, results of numerical simulation are presented, both in regular and irregular waves. In conclusion, range of distances for which it seems to be worth taking into account wave interactions or not are proposed.

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1. Methods

1.1. Equation of motion of two wave energy converters

Let us consider two basic arrays of wave energy converters, Fig. 1. The first array, array I, is composed of two semi-submerged cylinders and the second array, array II, of two semi-submerged rectangular shaped floating bodies. The diameter of each cylinder is taken equal to 10 m and their draught is equal to 10 m, corresponding to a displacement V_1 of around 785 m^3. It is assumed that both cylinders can move only in the heave motion z (i.e. along the vertical axis), with all other degrees of freedom ideally restricted. For the second array, the width and draught of the two bodies are taken equal to 10 m in order to have the same surface facing the waves and the length is taken equal to 7.85 m in order to have a volume similar as the one of the cylinders. Their motion is restricted to the surge motion x, all other degrees of freedom being ideally restricted. For both arrays, an idealised power take off (PTO) is considered, composed of a linear spring and damper system with stiffness k_{PTO} and damping coefficient b_{PTO}.

Let us note with index $_1$ and $_2$ all quantities related, respectively, to the first and with the second system in each array. Let z_1 and z_2 be the heave motion of each buoy in the first array, and x_1 and x_2 be the surge motions in the second one. Let $\mathbf{X}=(z_1\ z_2)^t$ (respectively $(x_1\ x_2)^t$) be the position vector of the whole array. Assuming the fluid to be non-viscid and incompressible, the flow to be irrotational, and the amplitude of motions and waves to be sufficiently small in comparison with the wavelength and the dimensions of the bodies, the classical linearised potential theory can be used as a framework for calculation of the fluid–structure interactions. Hence, one can write the equation of motion of the WEC in the frequency domain for unitary wave amplitude and a wave frequency ω:

$$(\mathbf{M}+\mathbf{AM}(\omega))\ddot{\mathbf{X}}+(\mathbf{B}_{PTO}+\mathbf{B}(\omega))\dot{\mathbf{X}}+(\mathbf{K}_H+\mathbf{K}_A+\mathbf{K}_{PTO})\mathbf{X}=\mathbf{F}_{ex} \quad (1)$$

with:

- $\mathbf{X}=\Re(\overline{X}e^{i\omega t})$ and $\dot{\mathbf{X}},\ddot{\mathbf{X}}$ being, respectively, the velocity and acceleration vectors of the WECs.
- $\mathbf{M}=\begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix}$ the mass matrix of the system. As it is considered identical bodies in each of both arrays, $m_1=m_2=785$ t.
- $\mathbf{K}_H=\begin{pmatrix} kh_1 & 0 \\ 0 & kh_2 \end{pmatrix}$ the hydrostatic stiffness matrix of the system. In the array composed of heaving cylinders, $kh_1=kh_2=770$ kN m^{-1}. In the array composed of surging barges, $kh_1=kh_2=0$ kN m^{-1}.
- $\mathbf{K}_A$ an additional stiffness matrix which represents the action of possible moorings. In this study, it was neglected, i.e. $\mathbf{K}_A=\mathbf{0}$ in both arrays.
- $\mathbf{AM}(\omega)=\begin{pmatrix} am_{11} & am_{12} \\ am_{21} & am_{22} \end{pmatrix}$ the added mass matrix and $\mathbf{B}(\omega)=\begin{pmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{pmatrix}$ the wave damping matrix which represent the radiation of waves by the body when it moves. In these matrices, the nondiagonal terms are not anymore equal to 0. They represent the pressure force measured on one body due to the radiated wave associated with a motion of the other one. For obvious symmetry reasons, $am_{11}=am_{22}$, $am_{12}=am_{21}$, $b_{11}=b_{22}$, $b_{12}=b_{21}$.
- $\mathbf{F}_{ex}=\Re(\overline{F}_{ex}e^{i\omega t})$ is the excitation vector per unit of wave amplitude, associated to the action of incident and diffracted wave fields upon the WECs.
- $\mathbf{K}_{PTO}=\begin{pmatrix} k_{PTO} & 0 \\ 0 & k_{PTO} \end{pmatrix}$ and $\mathbf{B}_{PTO}=\begin{pmatrix} b_{PTO} & 0 \\ 0 & b_{PTO} \end{pmatrix}$ are the matrices associated with the action of the PTOs. In array I, k_{PTO} is set equal to 0. In array II, k_{PTO} is tuned in order the surging barges to have the same natural frequency than the heaving cylinders of array I. For both arrays, the value of b_{PTO} has been tuned in order to achieve the maximum energy absorption at the natural frequency ω_0 of an isolated device. Following Falnes (2002), it has been set equal to the wave damping coefficient, i.e: $b_{PTO}=b_{isolated}(\omega_0)$.

In regular waves, the mean power extracted by each buoy in the array per unit of wave amplitude is given by

$$p_i=\tfrac{1}{2}b_{PTO}\omega^2|\overline{X_i}|^2 \quad (2)$$

with $i\in 1,2$. For the whole array, the mean absorbed power is

$$p=\sum_{i=1}^{2}p_i \quad (3)$$

In irregular waves, characterised by a wave energy spectrum S, the mean power extracted by each buoy is given by

$$P_i=\int_0^{+\infty}S(\omega)p_i(\omega)\,d\omega \quad (4)$$

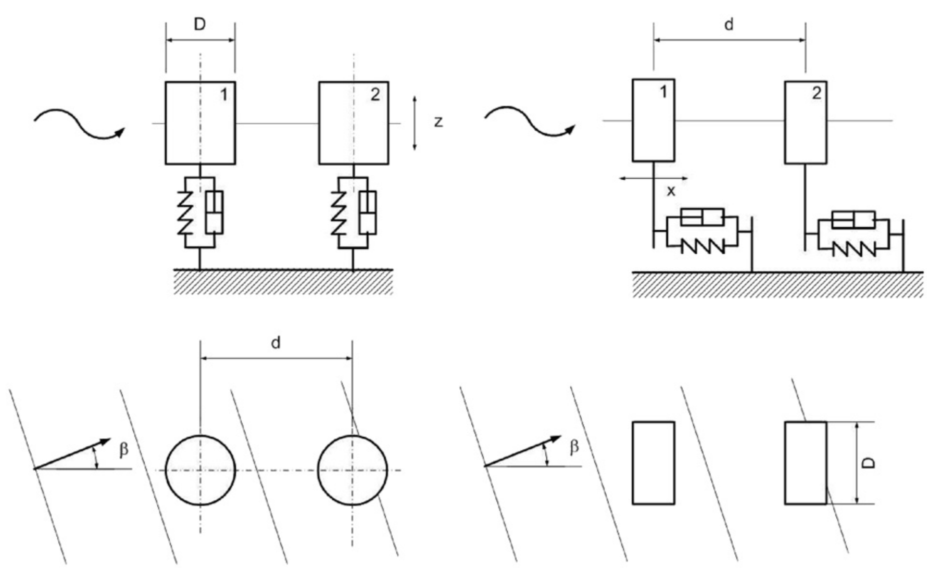

Fig. 1. Schematic representation of two arrays of generic wave energy converters. On the left, array I is composed of two heaving cylinders. On the right, array II is composed of two surging barges.