Renewable Energy 63 (2014) 55–68

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Wave-power absorption from a finite array of oscillating wave surge converters

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ARTICLE INFO

Article history:
Received 21 February 2013
Accepted 28 August 2013
Available online 25 September 2013

Keywords:
Wave energy
Wave-structure interaction
Arrays
Oscillating wave surge converter
Numerical modelling

ABSTRACT

Semi-analytical and fully numerical modelling is developed in the framework of the inviscid potential flow theory to investigate the dynamics of a wave farm made by flap-type wave energy converters in the nearshore. The hydrodynamic parameters and the efficiency of the system in typical layouts are calculated with both models. Good agreement is shown between the two approaches. Parametric analysis undertaken with the semi-analytical model allows to identify a near-resonant phenomenon which is responsible for increasing the absorbed power by the single elements of the array. Such result could be used as a preliminary design criterion. The numerical model is then applied to analyse a configuration of practical engineering interest, i.e. an array of two staggered converters. The dynamics arising in this more complex system is explained, showing that non-symmetric layouts can be less effective.

1. Introduction

Commercialisation of wave energy systems requires the deployment of wave energy converters (WECs) in large arrays as a fundamental market acceleration strategy. When working together in an array, WECs can interfere in either a constructive or destructive way, depending on the geometric layout and their mutual distance (see Refs. [1–10]). In this paper we investigate the dynamic interactions arising within an array of large flap-type WECs, namely the Oscillating Wave Surge Converters (OWSCs). Each OWSC is made by a flap hinged on a foundation at the bottom of the ocean and pitching under the action of incident waves in the nearshore [11]. Examples of OWSC at an advanced stage of design are the WaveRoller™ developed by AW Energy (http://aw-energy.com) and the Oyster 800™WEC developed by Aquamarine Power Limited (APL, www.aquamarinepower.com). In order to investigate the behaviour of an array of several OWSCs, four quantities are essential: the characteristic wave amplitude and wavenumber, A and k respectively, the characteristic width of the converters b and their mutual characteristic distance s. Various parameters can be formed from those quantities which are used to identify the regime of the system: A/b, kb, ks. First, in this paper we shall restrict our analysis to monochromatic waves of small-amplitude, for which $A/b \ll 1$. Second, we shall consider large flaps, so that $kb = O(1)$, and intermediate spacing between them, for which $ks = O(1)$. With the assumption $A/b \ll 1$, the behaviour of the system can be described by recurring to the linearised versions of the inviscid-irrotational equations of motion (potential-flow model, see for example Ref. [12]). Such hypotheses do not allow to consider either random-sea, vortex-shedding and nonlinear diffraction effects, which are currently being investigated with the aid of different models [13–17]. Yet the linearised potential-flow model provides an insightful description of the system dynamics which is fundamental for the successful design of such a costly project. Another important parameter to characterise the system regime is the product kb between the wavenumber of the incident wave and the characteristic width of the converters. Several existing analytical models are indeed applicable to the OWSC in the limiting cases $kb \ll 1$ and $kb \gg 1$. The first case corresponds to the so-called "point-absorber" approximation [1,3], while the second one refers to the "line-absorber" (terminator) limit [9]. However, considering an average OWSC width $b \simeq 30$ m and a characteristic wavelength $\lambda = 2\pi/k \simeq 100$ m (see for example Ref. [11]), yields $kb = O(1)$, which falls outside the limits of applicability of the aforementioned theories. Recently, new models in the regime $kb = O(1)$ have been developed to investigate the behaviour of an OWSC in a channel [18,19], an infinite array of OWSCs [20] and a single OWSC in the open ocean [21–23]. However, the analysis of a finite array of OWSCs seems not to have been undertaken yet. Indeed several

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http://dx.doi.org/10.1016/j.renene.2013.08.046

theoretical models are available to investigate the interactions in an array of floating bodies which are also implemented in numerical routines (see for example Refs. [5,24–30]). Some of these models rely on simplifying assumptions on the parameter ks. For $ks \gg 1$, the spacing between the elements can be neglected without appreciable consequences, as shown by Mei et al. [25] and Adamo & Mei [29] for an array of closely-spaced storm gates. On the other hand, when $ks \gg 1$ the wide-spacing approximation can be applied, for which radially outgoing waves are approximated as plane waves [5]. Here we shall consider the intermediate case $ks = O(1)$, where interference effects between the elements of the array must be appropriately accounted for [12].

In this paper, a twofold analytical and numerical approach is undertaken to investigate the dynamics of a finite array of OWSCs in the open ocean. In Section 2 a general mathematical model of the system is introduced and the governing equations are detailed. Then a new semi-analytical model for an in-line array of OWSCs in normally incident waves is derived. This model, yet necessarily based on some simplifying assumptions, provides a valuable physical insight on the system dynamics. In addition to the analytical approach, a finite-element model is presented to solve numerically the governing equations of the system for more general layouts. Then in Section 3 both models are validated. The dynamics of two and three in-line converters is discussed. For the first time, a near-resonant phenomenon – already known for arrays of floats – is shown to occur for an array of OWSCs. Hence the semi-analytical solution is employed in Section 3.2 to investigate the parametric behaviour of the system with respect to the period of the incident wave and the spacing between the flaps, showing potential for constructive interaction at near-resonant periods. Finally, in Section 4 the potential of the numerical model is applied to analyse a configuration of practical engineering interest, i.e. an array of two staggered OWSCs.

2. Mathematical model

2.1. Governing equations

Referring to Fig. 1, consider a system made by a finite number M of OWSCs in an ocean of finite depth h'. Let the primes denote physical quantities. Each OWSC is modelled as a rectangular flap of thickness a'_m and width w'_m, hinged on a bottom foundation of height c'_m, $m = 1, 2, \ldots, M$. Under the action of monochromatic incident waves of amplitude A'_I and period T', the flaps are able to perform a pitching motion, from which useful energy is extracted by means of linear power take-off (PTO) mechanisms linked to each device. Given the linearity of the system, all flaps oscillate with the same period T' but with potentially different phases, depending on the geometry. A Cartesian system of reference $O'(x', y', z')$ is set at an arbitrary origin O' on the still water level $z' = 0$, with the centreline of each flap aligned with the y' axis and the z' axis pointing vertically upwards (see again Fig. 1). Assume that the mth flap is able to perform oscillations of angular amplitude $\theta'_m(t')$ about the y' axis at $z' = -h' + c'_m$; t' is time. Now let $\mathscr{L}'_m$ denote the region occupied by the mth flap at the equilibrium position (i.e. $\theta'_m = 0$) and let $\partial\mathscr{L}'_m$ be its solid boundary. Assume that the fluid is inviscid and incompressible and the flow irrotational. Then there exists a potential Φ' for the velocity field $\mathbf{v}' = \nabla'\Phi'$ which satisfies the Laplace equation

$$\nabla'^2\Phi'(x', y', z', t') = 0 \tag{1}$$

in the fluid domain. In (1), $\nabla' f' = (f'_{x'}, f'_{y'}, f'_{z'})$, where subscripts here denote differentiation with respect to the relevant variables. Assuming that the flaps perform small-amplitude oscillations, the set of boundary conditions (b.c.'s) associated to the Laplace equation (1) can be linearised as shown in Ref. [19] thus yielding

$$\Phi'_{t't'} + g\Phi'_{z'} = 0, \quad z' = 0 \tag{2}$$

for the kinematic–dynamic b.c. on the linearised free-surface,

$$\Phi'_{z'} = 0, \quad z' = -h' \tag{3}$$

for the no-flux condition at the bottom and finally

$$\Phi'_{\hat{n}} = V'_{m\hat{n}}, \quad \text{on } \partial\mathscr{L}'_m, \quad m = 1, 2, \ldots, M \tag{4}$$

for the kinematic b.c. on the flaps. In the latter expression, $V'_{m\hat{n}}$ is the component of the mth-flap velocity along the normal $\hat{n} = (n_{x'}, n_{y'}, n_{z'})$ directed out of the fluid on the boundary $\partial\mathscr{L}'_m$ [12]. Hence for pitching motion about the y' axis, expression (4) yields

$$\Phi'_{x'} = -\theta'_{m,t'}(t')(z' + h' - c'_m)H(z' + h' - c'_m), \quad m = 1, 2, \ldots M, \tag{5}$$

along the flap sides normal to the x' axis, where the Heaviside step function H assures absence of flux through the bottom foundation, and

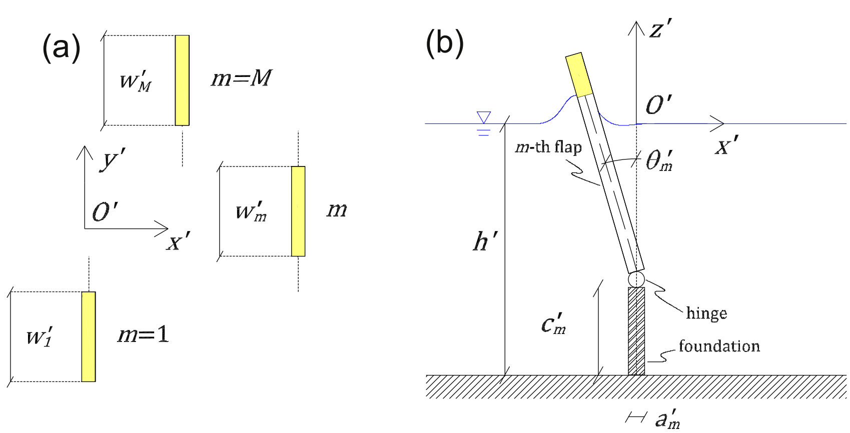

Fig. 1. Geometry of an array made by M OWSCs. (a) Plan view, (b) section of the m-th OWSC.