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Hydrodynamic and energetic properties of a finite array of fixed oscillating water column wave energy converters

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ABSTRACT

Farms of wave energy convertors are more likely to be deployed than widely separated individual devices so as to harness maximum available power and to facilitate installation and electrical power transmission. In this paper, the theory of the interaction between oscillating systems, developed by Falnes and McIver (1985), is for the first time applied and extended to an explicit study of the dynamic and energetic performance of a finite array of fixed OWC devices. The interactions between devices and air compressibility are taken into account. Following the method, a FEM model is applied to the study of a single OWC device and three different array configurations. It is demonstrated that the inner properties and the interaction between OWC devices are strongly dependent on the position of the devices in the array and should be taken into account when determining the optimum device parameters so as to increase the maximum power extraction of the system or the overall frequency power-capture bandwidth.

1. Introduction

Over the past two decades nations worldwide have been looking for new energy sources in order to slow down the effects of climate change induced by the extensive use of fossil fuels. A large number of renewable energy sources are currently being researched, developed and applied. There are six main areas of renewable energy technology: bioenergy, direct solar energy, geothermal energy, hydropower, ocean energy and wind energy. An overview of these technologies can be found in the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN), IPCC (2011), released by the Intergovernmental Panel on Climate Change (IPCC).

Ocean energy can be further categorized into wave energy, tidal range, tidal currents, ocean currents, ocean thermal energy conversion and salinity gradient. As presented in Lewis et al. (2011), the overall potential of ocean energy exceeds the present worldwide energy requirements. In this report, wave energy alone was estimated to be around twice the overall electricity supply in 2008, making it a significant clean source of energy. Unlike the case with wind energy technologies, which are relatively well developed, efficient extraction of the energy stored in ocean waves is a key issue that still requires very significant research and development effort before this renewable resource can be economically exploited. More than 50 different conceptual system designs have already been investigated, but only a handful of these have been tested at full scale. Reviews of these technologies can be found in Clément et al. (2002), Cruz (2008), Falnes (2007), Khan and Bhuyan (2009) and Falcão (2010). With the help of government initiatives, wave energy technology is developing quickly around the world. As an example, the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) released an analysis, (CSIRO, 2012), stating that wave energy could contribute up to 11 per cent of total Australian electrical power by 2050. Recently, three Australian wave energy companies Carnegie Wave Energy Ltd., Oceanlinx Ltd. and BioPower Systems Pty Ltd. were granted funds from the Australian Renewable Energy Agency, (ERP, 2012), to support pilot projects around Australia.

As the technology develops further, farms of Wave Energy Convertors, instead of single devices, will likely be deployed. Nader et al. (2012) highlighted the complexity of interactions between multiple OWC devices within finite arrays of these systems. Spacing between devices relative to the incident wavelength, as well as the incident angle of the incoming wave, can strongly influence the energetic behaviour of the system. Investigation of the influence of the pneumatic damping coefficient on system performance also showed that optimum coefficients for each of the devices might differ from that of an isolated device. However, Nader et al. (2012)

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did not fully investigate the optimisation of the pneumatic damping coefficient for maximum energy extraction. Moreover, following Evans and Porter (1997), the pneumatic damping coefficient was considered positive and real. Such assumptions overlook the effect of air compressibility inside the OWC chamber. As shown by Sarmento and Falcão (1985) and subsequently by Martins-Rivas and Mei (2009a, 2009b), air compressibility can have a non-negligible effect on the power extraction of an OWC device.

Falnes and McIver (1985) developed a theoretical model of the interaction between oscillating wave energy systems. In this paper, we analyse a finite array of fixed OWC devices. In contrast to Falnes and McIver (1985), the coupling between the pressures and the volume fluxes are expressed by considering that a Wells type turbine is used as the power take-off system. The influence of air compressibility on these OWC devices is taken into account. It is shown that only a set of frequency dependent hydrodynamic coefficients is needed to model the dynamic and energetic behaviour of the system. The hydrodynamic coefficients are then computed using a newly developed 3D FEM model for a Single Isolated OWC Device (SIOD) and three different array configurations, i.e. a column of two identical cylindrical OWC devices, a row of two identical cylindrical OWC devices, and a square array of identical cylindrical OWC devices. Special attention is also given to the optimisation of the turbine parameters in order to obtain maximum hydrodynamic power absorption.

The present paper is separated in four main sections. First, the general boundary conditions and analysis for an arbitrary number of fixed OWC devices are formulated. The theoretical model of the interaction between oscillating systems is then applied to four specific array configurations. Numerical approaches including the FEM model used to solve the system, the method to calculate the hydrodynamic coefficients and the numerical optimization algorithm are described. Finally, results are presented and discussed.

2. General formulation

2.1. System

We start by considering a system consisting of a number n of fixed OWC wave energy converters of arbitrary shape. The OWC devices are randomly numbers from 1 to n. Linear water-wave theory with irrotational and inviscid flow is assumed. A Cartesian coordinate system (x,y,z) with its corresponding cylindrical coordinates (r,α,z) are situated at the mean sea water level, the z-direction pointing vertically upwards. A monochromatic plane wave of amplitude η_0, frequency ω and phase ψ propagates with an incident angle θ to the x-axis. The computational domain is separated into two regions with constant water depth h, an outer region between a radius of r_1 and r_2 with a complex velocity potential ϕ_a, and an inner region within the radius r_1 with a complex velocity potential ϕ_b. The inner region is considered to contain all the OWC devices. Both potentials satisfy the Laplace equation

$$\nabla^2\phi_a = 0 \tag{1}$$

and

$$\nabla^2\phi_b = 0. \tag{2}$$

The velocity potential ϕ_a can be decomposed into the sum of the incident wave velocity potential ϕ_i and the velocity potential ϕ_s induced by the scattering of the wave by the array,

$$\phi_a = \phi_s + \phi_i \tag{3}$$

where

$$\phi_i = -\frac{ig}{\omega}\eta_0 \frac{\cos\,hk(z+h)}{\cos\,h\,kh} e^{ik(x\,\cos\,\theta + y\,\cos\,\theta)}. \tag{4}$$

In this expression, g is the gravitational constant and the wave number k is equal to $2\pi/\lambda$. The parameter λ is the wavelength. The wave number k satisfies the dispersion relation

$$\omega^2 = gk\,\tan\,h(kh). \tag{5}$$

In order to model the effect of the turbine, dynamic pressures inside each of the OWC chambers are assumed to oscillate at the same frequency as the incident wave. The complex values of these pressures can be introduced and the pressure $P_c^{[l]}$ inside the OWC device number l can be expressed as

$$P_c^{[l]} = \mathrm{Re}\{p_c^{[l]} e^{-i\omega t}\}. \tag{6}$$

2.2. Boundary conditions

The general boundary conditions for this problem are

- In the outer domain $r_1 \le r \le r_2$
  On the sea floor at $z = -h$

$$\frac{\partial\phi_s}{\partial z} = 0. \tag{7}$$

On the surface, at $z = 0$

$$\frac{\partial\phi_s}{\partial z} - \frac{\omega^2}{g}\phi_s = 0. \tag{8}$$

And the Sommerfeld radiation condition on r_2 when r_2 tends to infinity

$$\sqrt{r}\left(\frac{\partial\phi_s}{\partial r} - ik\phi_s\right) = 0. \tag{9}$$

- The matching boundary condition between the two regions at $r = r_1$

$$\phi_b = \phi_s + \phi_i \quad \text{and} \quad \frac{\partial\phi_b}{\partial r} = \frac{\partial\phi_s}{\partial r} + \frac{\partial\phi_i}{\partial r}. \tag{10}$$

- In the inner region $r \le r_1$
  At any point on the walls of the devices

$$\frac{\partial\phi_b}{\partial n_N} = 0, \tag{11}$$

where $\partial/\partial n_N$ is the derivative in the direction of the unit vector n_N normal to the surface of the walls and pointing outward of the fluid.

On the surface outside the OWC chambers, at $z = 0$

$$\frac{\partial\phi_b}{\partial z} - \frac{\omega^2}{g}\phi_b = 0. \tag{12}$$

On the surface $S_i^{[l]}$, created by the water at rest inside the chamber of the OWC device number l,

$$\frac{\partial\phi_b}{\partial z} - \frac{\omega^2}{g}\phi_b = \frac{i\omega p_c^{[l]}}{\rho g}, \tag{13}$$

where ρ is the density of the water (cf. Evans and Porter (1997)).

2.3. Turbine characteristics and dynamic pressures

The dynamic pressures inside each of the OWC devices are considered to be proportional to their respective volume fluxes. By considering air compressibility, as in Sarmento and Falcão (1985), the relationship between the dynamic pressure $p_c^{[l]}$ and volume flux $q^{[l]}$, inside the chamber of the OWC device l can be expressed