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The modular concept of the Oscillating Wave Surge Converter

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ABSTRACT

In this study, we discuss the hydrodynamics of the modular concept of a well known wave energy device - the Oscillating Wave Surge Converter. Such a concept has emerged to address some of the shortcomings in the original design of the device. A mathematical model is presented to analyze the effect of the interactions of the system. The analysis is performed with a modular system comprising of six identical modules of total combined width 24 m, reminiscent of the Oscillating Wave Surge Converter - Oyster800 developed by Aquamarine Power. Various design strategies are explored. It is shown that such a closely packed system of modules results in multiple resonances which can potentially be exploited to capture more power. It is also observed that the modules lying at the center of the system capture more energy than those lying at the edges. An optimization of power take-off system shows that at lower wave periods it is possible to capture the levels of power similar to those of an equivalent size rigid flap while at higher periods, the modular system has the potential to capture more energy due to the occurrence of multiple resonances.

1. Introduction

The Oscillating Wave Surge Converter (OWSC) is already recognised as a robust and efficient wave energy conversion device. By nature of its operating principles, the OWSC concepts are largely nearshore based as they try to exploit the amplification in the horizontal surge motion of the water particles in shallow waters [1]. One of the best known OWSC is the Oyster device developed by Aquamarine Power. It is a wide flap which captures energy by performing pitching motion about a horizontal hinge axis located at some distance above the sea bed and ideally located in water depths of 10–15 m. The design of this wave energy converter (WEC) has evolved significantly since its inception and a lot of research is still focussed on modifications which can address some of its shortcomings. One of the disadvantages of having a single flap of such large width is the large wave loads acting on the common foundation at the bottom especially in extreme wave conditions which have been observed on the Oyster800 prototype installed at the European Marine Energy Centre test site, Orkney, Scotland. A possible mechanism to mitigate such destructive effects is to divide the flap into smaller components. A new concept that has emerged based on the above philosophy is a modular form of the OWSC (see [2]), which is analyzed in this paper (see Fig. 1). In fact, experimental results presented in Ref. [2] show a reduction in the parasitic foundation loads such as the yaw and roll twisting moments. In addition to this, the breakdown of the structure can potentially help in its fabrication and installation. However, it is not yet understood how such a design alteration would impact the hydrodynamics and performance of the OWSC system.

The studies on Venice gates were probably the first investigations on the behavior of ocean based modular systems (see e.g. Refs. [3–5]). The purpose of these barriers is to control the flooding of the Venice lagoon and they are at present under construction. The research work on the gates was mostly focussed on understanding the subharmonic resonance of the system of gates which resulted in large out-of-phase oscillations of the coupled gates. A linear theory was developed in Ref. [3] to explain the resonant phenomenon which occurred at half the frequency of the incident wave and was verified with experimental findings as well. Later the method was extended in Ref. [6] to examine inclined gates using a hybrid element method. In Ref. [7], the natural modes of a long barrier comprising of a sequence of discrete gates were determined, while in Ref. [8] the gate system was analyzed in a

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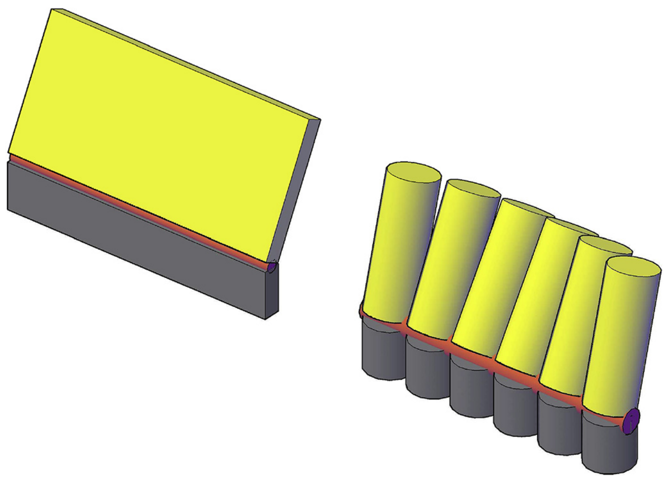

Fig. 1. A 3D graphical illustration of a rigid flap and a modular flap-type WEC.

semi-channel open to the sea. Recently, the potential of exploiting the subharmonic resonant mechanisms in harnessing energy was explored in Ref. [9]. However, the resonant phenomenon depends strongly on the parameters e.g. the inertia of the gates, incident wave frequency, water depth. This sensitivity limits the application of the system to a real ocean environment. The key differences between the modular gate system and the modular flap system discussed in this study include their purpose, their dimensions (width of each modular gate similar to a rigid OWSC) and their application in different layouts (gates in a channel, OWSC in the open ocean).

The hydrodynamics of a single wide OWSC has been studied extensively since the initial works of Refs. [10–13], and is well understood now. An abundant theoretical literature now exists on it, starting from understanding its behavior in a channel [14], in the open ocean [15], along a straight coast [16], to that in arrays [17,18] and in a wave farm [19]. The analysis is based on approximating the wide flap as a thin-rigid plate. Such a hypothesis is based on the assumption that the thickness of the flap is much smaller than its width. However, when the flap is divided into modules, each of them has a width comparable to its thickness and therefore the thin-plate approximation can no longer be applied in such circumstances. To analyze the concept of modular flaps, we approximate each of the components as cylinders. The hydrodynamics of an isolated large cylindrical bottom-hinged flap type WEC was already studied in Ref. [20], where use was made of the relative velocity Morison equation, and force coefficients were obtained from radiation and diffraction theory.

In the case of the modular OWSC, an appropriate modeling of the interactions within the closely packed system needs to be undertaken. The general philosophy of the present analysis is based on the multiple body interaction theory of [21], which uses the addition theorems of Bessel functions. A similar technique had previously been adopted to model interactions among heaving truncated cylindrical systems [see e.g. 22, 23]. In this study, first we develop a mathematical model for the analysis of the system shown in Fig. 2. In §3, computations are performed for some possible power take-off strategies, along with a discussion of the general hydrodynamics and the multiple resonant characteristics of the modular system. In §4, an optimization of the power take-off damping coefficients is performed using genetic algorithm. And lastly, in §5, the same modular system with a gap underneath is considered and analyzed by using the mathematical model of [22].

2. Mathematical model

The modular flap-type WEC is considered to be situated in an ocean of constant water depth h', and comprises of a total of M modules. The incoming waves of amplitude A'_I are considered to be obliquely incident making an angle ψ with the negative x'-axis. Each of the modules independently performs oscillatory motion about a horizontal hinge which is located at a distance c' above the sea bed. The fluid is considered to be inviscid and incompressible, and the flow irrotational. Therefore there exists a velocity potential Φ' which satisfies the Laplace equation in the fluid domain. The scalar potential also satisfies the linearized kinematic-dynamic free surface boundary condition

$$\Phi'_{,t't'} + g\Phi'_{,z'} = 0, \quad z' = 0, \tag{1}$$

where g is the acceleration due to gravity, and the no-flux boundary condition on the sea bed

$$\Phi'_{,z'} = 0, \quad z' = -h'. \tag{2}$$

The individual modules of the WEC are modeled as cylinders and the kinematic boundary condition on them yields

$$\Phi'_{,r'_j} = -\theta_{j,t'}(z' + h' - c')H(z' + h' - c')\cos\xi_j, \quad r'_j = a'_j, 0 < \xi'_j < 2\pi, \tag{3}$$

where H is the Heaviside step function. The non-dimensional system of variables is chosen as

$$(x, y, z, r_j) = \left(x', y', z', r'_j\right)/h', \quad t = \sqrt{\frac{g}{h'}}t', \quad \Phi = \frac{\Phi'}{\sqrt{gh'}A'_I}, \quad \varepsilon\theta = \theta', \tag{4}$$

where $\varepsilon = A'_I/h'$ is the small parameter of the problem. Assuming the motion to be simple harmonic in nature, we obtain

$$\theta_j = Re\left\{\Theta_j \exp^{-i\omega t}\right\}, \quad \Phi = Re\left\{\phi(r_j, \xi_j, z)\exp^{-i\omega t}\right\}, \tag{5}$$

where $\omega = \omega'\sqrt{h'/g}$ and Θ_j are respectively, the angular frequency and amplitude of oscillation of the j-th module, while $\phi(r_j,\xi_j,z)$ is the complex spatial velocity potential in the co-ordinate system of the j-th module. In order to analyze the modular WEC, we first determine the scattering matrices of an isolated module and then use them to obtain the solution for an array of such bodies. The methodology is similar to that in Ref. [22], with a system of heaving truncated cylinders.

2.1. Isolated module

For an isolated module, the coordinate system is located at its center. The spatial velocity potential ϕ is decomposed into the scattering potential $\phi^{(S)}$ and radiation potential per unit velocity $\phi^{(R)}$ as follows

$$\phi = \phi^{(S)} + V\phi^{(R)} = \left(\phi^{(I)} + \phi^{(D)}\right) + V\phi^{(R)}, \tag{6}$$

where, $\phi^{(I)}$ is the incident wave potential, $V = i\omega\Theta_0$ is the complex angular velocity of the isolated module, and $\phi^{(D)}$ is the diffracted wave potential. In our description, the subscript index $j = 0$ will be used to indicate the behavior of the module in isolation (i.e. no other module is present). The general form of the spatial potential for the radiation (R) and the scattering (S) problem can be written as