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Modelling of the multi-chamber oscillating water column in regular waves at model scale

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Abstract

This paper studies the reliability of numerical models used for estimating multi-chamber oscillating water column (MC-OWC) response in the time-domain. The model for the internal water surface level and instantaneous pressure inside the chamber at regular waves conditions using a hybrid system of hydrodynamic and thermodynamic rigid piston models without power take-off. Reliability is assessed using experimental data obtained from a wave tank used in the model concept validation. The results show the method could be extended to describe the hydrodynamics of the MC-OWC in regular and irregular wave conditions.

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Keywords: Oscillating water column; renewable energy; wave energy

1. Introduction

Renewable energy sources have a fundamental role in the reduction of air pollution, especially CO_2 emission. Among the renewable energy resources, ocean wave energy is still an emerging technology which is still largely untapped, and the potential for extracting energy from it is considerable. It is estimated that between 2000 and 4000 TWh per year of energy can be extracted worldwide from waves [1]. Ocean wave energy contains roughly 1000 times the kinetic energy of the wind, and should be harvested with much smaller and less conspicuous devices to

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produce the same power in the same available space. There are more than one hundred prototypes of various wave energy converter (WEC) systems [2], particularly in oceanic countries such as Ireland, Denmark, Portugal, U.K., U.S.A., and Australia. Several pre-commercial ocean devices have been deployed. The WEC design and development process extends from applying fundamental laws of physics at the initial concept proving stage to commercial demonstration. These processes have been found to be difficult, slow and expensive [3]. To circumvent these barriers several approaches and comprehensive programs have been proposed and implemented. There is no agreed approach to the development and evaluation of WECs. However, the technology readiness level (TRL) is considered to be a standard approach for engineering application and industrial development. TRL is a proposed program for advancement in the design and development of WECs [4]. The TRL approach can be divided into five main stages [5]: Concept Validation (TRL1-3), Model Validation (TRL4), System Validation (TRL5-6), Device Validation (TRL7-8), and Economics Validation (TRL9). The MC-OWC comprises of several chambers that divide the wave into sections and allow each chamber to run as an OWC as shown in Fig. 1. The pumped air flow that results from the change of the internal water surface in each chamber will drive the installed turbines between chambers. In the device studied here, there are four chambers.

Fig. 1. Scale model of MC-OWC.

In previous work, the initial verification of the model concept was performed using single-frequency regular waves of small amplitudes. This is considered as the first part of stage TRL1-3 in the TRL approach. Small amplitude linear wave theory assumptions were used to evaluate the power measurement and some basic parameters such as the effect of the water surface elevation and area ratio and its influence on device performance characteristics [6]. Then the capture width was studied, which is considered as the most common parameter used to define the performance of a WEC. After these stages, the basic operation of a device has been observed. The experimental data of the proposed model are ready to use for validation and calibration of the mathematical model which is used in this work [7]. After the initial verification of the models, the next step of the development and design process includes many expensive experimental studies involving numerical simulations and large-scale testing.

Amongst the number of numerical models used to analyze and simplify the interaction between waves and WECs (which include analytical methods, boundary integral equation methods), the Navier-Stokes equations and empirical methods are often used. Analytical methods that depend on a system of hydrodynamic and thermodynamic analysis are widely used to understand the interaction between waves and device bodies on a variety of WECs. The aim of this paper is to present such a single chamber OWC numerical simulation designed on Matlab/Simulink, describing the energy chain from the ocean waves to the pneumatic power extracted. The proposed model uses the hydrodynamic efficiency, the water surface level, the air velocity inside the chamber, and the air pressure as indices to evaluate the energy capture efficiency of the OWC. The simulation results are used to define the optimal design of the MC-OWC based on the wave tank conditions, to the evaluation of hydrodynamic characteristics.

2. Hydrodynamic modeling

Theoretical and numerical studies of the hydrodynamic process in WECs are difficult due to relative complex diffraction and radiation wave phenomena, so it must be fully understood [3]. The TRL approach shows that successful design and optimization of WECs must be based on theoretical modeling during the pre-conception stages [8, 9]. Theoretical and numerical modeling of WECs has achieved substantial progress during different stages of development; this leads to understanding of the model behavior and reduction of the development time and construction cost and risk. The main purpose of hydrodynamics modeling is to understand the interaction between waves and device bodies. Two models were presented to model the hydrodynamics of OWC devices; the first one is the massless piston model, and Evans [10] was one of the first to use a simple approximate analytical of the rigid-body theory to obtain the efficiency of various shapes for wave energy absorption. In the next stage of modeling development, the motion of water surface level inside the chamber is assumed to act as a light piston. After that, the rigid piston approach was improved by Falcão and Sarmento [11]. Finally, a rigid piston approach was generalized and it is considered as the more accurate model that describes the hydrodynamics of the OWC devices; it also has the advantage of producing simpler boundary value problems that are more easily solved [12]. The second model was called a pressure distribution model which describes the hydrodynamic behavior of the OWC in term of dynamic air pressure inside the chamber. The pressure distribution inside the OWC chambers is a major factor in wave energy capture efficiency [10]. Recently, a hybrid system of the hydrodynamic and thermodynamic is used to govern the internal water surface level and the instantaneous pressure inside the chamber for regular and irregular wave's conditions. The internal water surface level and the instantaneous pressure inside the chamber are considered as crucial parameters of WEC design and development. The latter model is used in this paper; this has the same assumptions as the model in [13]. The model approach uses the work on trapped air cavities for the marine vehicles.

Due to the small-scale structure that used in this stage of development, wave field diffraction is neglected and the flow field is considered as a two-dimensional irrational flow. Moreover, vortex and viscous effects which may occur inside the chamber are not considered. Therefore linear wave theory is used to represent the incident wave. The vertical displacement of the free surface is $\eta(x,t)$, and is derived from small amplitude wave theory [14] in (1).

$$\eta(x,t) \approx \frac{1}{2} H \cos(kx - \omega t) \tag{1}$$

$$\left(M + M_a\right)\frac{d^2\eta}{dt^2} + B\frac{d\eta}{dt} + K\eta = f(t) \tag{2}$$

The exciting wave force and the wave surface elevation are used to generate the time series of the exciting wave forces. The time domain added-mass and damping coefficients, time series of wave exciting forces, device dimensions, and use of the orifice assumption as PTO, are used to solve the equations of motion to determine the internal water surface level, the instantaneous pressure inside the chamber, and the air flow velocity. Finally, these parameters used to generate the time series of the pneumatic power output.

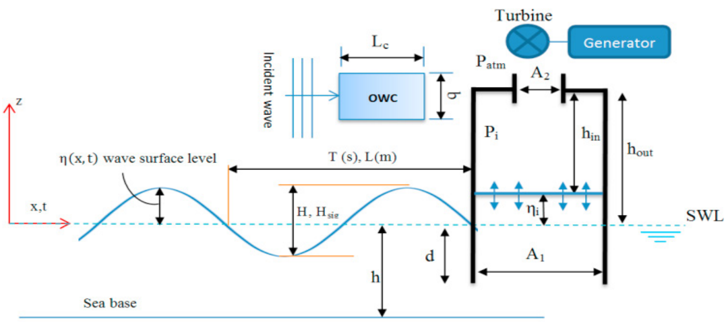

Fig. 2. Schematic representation of the numerical model OWC.

The governing equation of the rigid piston model that describes a motion of the fixed-structure OWC in terms of the external forces, mass, damping, and restoring properties is derived from Newton's second law. The linearized equation of motion in heave (see Fig. 2) can be described by (2) above where M is the mass of the column of water (kg) at the still water level (SWL), which can be defined as in (3). M_a is the added mass (kg) which is considered as a difficult characteristic to determine due to inflow/outflow variations caused by the incident wave; it can be calculated by assuming the added volume of the rectangular chamber is a function of the area of the internal free surface area of the chamber and the density of water. It expressed in (4).

$$M = \rho_w \times A_1 \times d \tag{3}$$

$$M_a = \rho_w \times A_1 \times \eta \tag{4}$$

B in (2) is the air damping caused by pressure drop, A_1 is the chamber area, ρ_w is the water density and d is the length of the wet surface of the chamber at SWL as illustrated in Fig. 2. B is hard to model, so assume the restored coefficient be 10 % of critical and hydrostatic stiffness; hence, the damping coefficient B can be simplified to (5). Finally, K is the hydrostatic restoring coefficient attributed to hydrostatic pressure as illustrated in (6).

$$B = 0.2 \times \sqrt{K\left(M + M_a\right)} \tag{5}$$

$$K = \rho_w \times g \times A_1 \tag{6}$$

The pressure P_c inside a chamber and air volume V_a both have a small value due to use a small-scale model. The air density through the orifice plate is assumed to be constant due to the small chamber volume and assumed incompressible. Therefore, the mass change rate is purely caused by the change of the air volume, and the flow rate through the power take-off system (PTO) is

$$\dot{m} = \rho\, dV/dt \tag{7}$$

The left-hand side of (1) is the total forces $f\,(t)$ that acts on the water column. It is made up of three forces as shown in (8) where $F_a\,(t)$ is the added mass force which acts as the damping force and is defined in (9).

$$f(t) = F_{FK}(t) - F_a(t) - F_{\Delta p}(t) \tag{8}$$

$$F_a(t) = M_a \times \left(\frac{\partial^2 \varphi}{\partial t^2} - \frac{\partial^2 \eta}{\partial t^2}\right) \tag{9}$$

$\partial^2\varphi/\partial t^2$ is the vertical component of the water particle velocity which can be determined by

$$\dot{w} = \frac{\partial^2 \varphi}{\partial t^2} = \omega^2 \frac{H}{2} \frac{\sinh\left[k\left(h-d\right)\right]}{\sinh kh} \times \cos\left(\omega t + \theta\right) \times \frac{2}{\theta} \times \sin\left(\frac{\theta}{2}\right) \tag{10}$$

where H is the wave height in m, θ is the angular length of the chamber $=2\pi L_c/L$ where L is the incident wavelength and L_e is the single chamber length , k is the wave number and $= 2\pi/L$, ω is the angular wave frequency $= 2\pi/T$ where T is incident wave period in s, h is water depth in the wave tank at SWL, see Fig.3. The Froude-Krylov force term $F_{FK}(t)$, which is generated by the pressure field that is acting on the bottom of the water column and drives the water upwards, can be represented by (11), where $P_{wave}\,(t)$ is the dynamic pressure field in a wave as given in (12).

$$F_{FK}(t) = P_{wave}(t) \times A_1 \tag{11}$$

$$P_{wave}(t) = \rho g \frac{H}{2} \frac{\cosh\left[k\left(h-d\right)\right]}{\cosh kh} \times \cos\left(\omega t + \theta\right) \times \frac{2}{\theta} \times \sin\left(\frac{\theta}{2}\right) \tag{12}$$

$F_{\Delta p}$ (t) is the variation of air force in the chamber which is defined by

$$F_{\Delta p}\left(t\right)=\Delta P\left(t\right)\times A_{1} \tag{13}$$

and ΔP is the difference between the inside chamber and atmospheric pressure. ΔP is determined by the thermodynamic part of the modeling.

The equations of motion need to be rewritten such that the right-hand side does not include the accelerations. Therefore, the governing equation of motion that describes the motion of water column in the regular wave is

$$\ddot{\eta}(t)=-\left(\frac{0.2}{d}\sqrt{g(d+\eta(t))}\right)\dot{\eta}(t)-\frac{g}{d}\eta(t)+\frac{\zeta}{d}-\frac{\Delta P(t)}{\rho_{w}\times d} \tag{14}$$

where

$$\zeta=\left(-g\times\frac{\cosh\left[k\left(h-d\right)\right]}{\cosh(kh)}-\eta\times\omega^{2}\times\frac{\sinh\left[k\left(h-d\right)\right]}{\sinh(kh)}\right)\times\frac{H}{2}\times\cos\left(\omega\cdot t+\theta\right) \tag{15}$$

In the second parts of the modeling, the ideal gas equation is used to describe the periodic pressure change (compression and expansion) inside the chamber. As described in [13, 15] the air density in the chamber is linear with the chamber pressure and considered as isentropic. The govern equation of the pressure change inside the chamber can be described by (16) where C_d is the coefficient of discharge which is assumed to be ≈ 0.5 for the small value of the area ratio (A_2/A_1), A_2 is the orifice area, ρ_{air} is air density, R is the ideal gas constant which equal to 287.1 J/kg.K for dry air, T is the ambient temperature in Kelvin which is 293 K, $P_c(t)$; is the instantaneous pressure inside the chamber, h_{a0} is the height of the top cover of chamber relative to SWL as illustrated in Fig. 2, and the pressure change $\Delta P(t) = P_c(t) - P_{atm}$. Due to the previous assumption, the output pneumatic power that the OWC device generates as a linear relationship between the chamber pressure and the mass flow rate at the orifice. This relationship can be defined equal to (17).

$$\Delta\dot{P}=\frac{R\times T\times C_{s}^{2}\times A_{2}}{A_{1}\left(h_{a0}-\eta\right)}\sqrt{2\times\Delta P\times\rho_{air}}+\frac{P_{c}}{h_{a0}-\eta} \tag{16}$$

$$P=\dot{m}\frac{\Delta p}{\rho_{air}} \tag{17}$$

3. Model validation and results

To verify the numerical model, a systematic comparison between the experimental data from the small-scale model performances under wave tank conditions, as illustrated in Table 1, and the predicted numerical simulation results for a single chamber with rectangular cross section rather than four chambers, which has been developed using MATLAB/Simulink. The validation of the equation of motion is done for the single fixed chamber which has fixed ratio of chamber area to orifice aperture area ($A_1/A_2 = 52$). This value of area ratio was used in the first stage of development and has produced a peak power compared with other ratios under the same wave tank conditions [6].

The results are calculated using time-dependent variables namely, internal water level η (t), pressure differential$\Delta p(t)$, volumetric flow rate through the orifice $V_a(t)$ and the converted pneumatic power $P_a(t)$, of the time-dependent variables.

Table 1 Characteristics of the wave tank [7]

Wave period [s]	5	1.6	1.25	1.12	1
Wavelength [m]	10.92	3.245	2.174	1.79	1.47
Average wave height [m]	≈ 0	0.044	0.086	0.087	0.088
Average wave power [W]	≈ 0	0.72	2.36	2.22	2.10

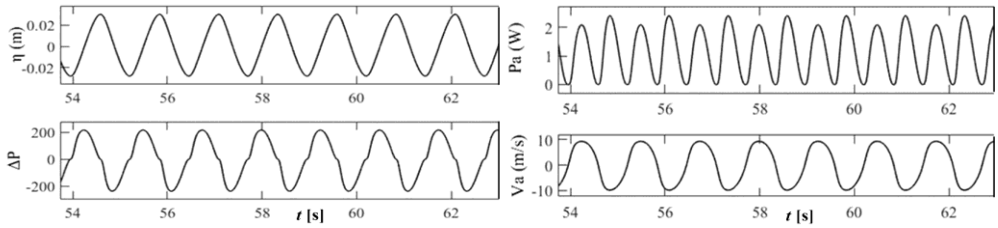

Fig. 3. Time series of the incident wave, inner surface elevation η, pressure change ΔP, pneumatic power Pa and air flow velocity at an aperture of the turbine Va. at incident wave condition (H = 0.086 m, T = 1.25 s).

Fig. 4 presents the response of the water surface level inside the chamber $\eta(t)$, the comparison of numerical and the experiment results for a wave period range of T = 1, 1.2 and 1.25 s. Although the simplification is applied to the nonlinear term of the wave condition in the numerical model, the numerical result shows a good agreement with the experimental results of the scale model at different wave periods and incident wave amplitudes. There is a variation in the results agreement. The closer numerical results to the actual experimental results will be at T = 01.12 s and incident wave amplitude H = 0.087 m as seen in Fig. 4(b). These differences may be due to the wave tank characteristic that was used in the experiment work. It has 4 m length which is not long enough to allow the incident wave propagate smoothly before it passes through the model. This behavior of the incident wave caused a turbulence and vortices effects in the chamber and around the wet wall, which are not taken into account by the numerical model. There is a phase shift in the wave surface elevation between the numerical and experimental results which lead to high relative error. Fig. 5 presents the air flow velocity at the aperture of the turbine duct (orifice A_2) for a range of wave period that available in the experimental condition. The experimental results are in good agreement with the numerical prediction, with a relative error around 6 %. The air flow velocity is one of the main parameters that determine the pneumatic power of the device as in (17). Therefore, the air flow agreement is considered one of the major advantages of the numerical model.

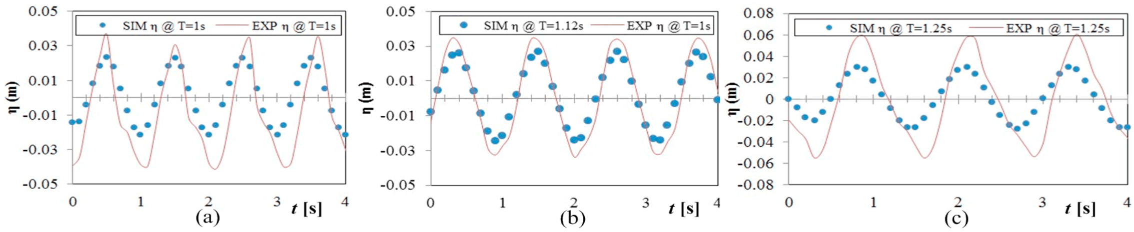

Fig. 4. Comparisons between simulation and measured internal surface elevation for a monochromatic wave with (a) T = 1 s, H = 0.088 m; (b) T = 1.12 s, H = 0.087 m; (c) T =1.25 s, H = 0.086 m.

During the stage of concept verification (TRL1-3), the total power was considered as two terms; the first term is due to the air flow velocity which was measured by an anemometer with a real time data logger. The second term is due to the air pressure difference across the turbine (P_P); the equations were illustrated in [7]. The derivation of P_P is based on the Bernoulli's equation in the previous work, which describes the relation between air flow velocity and the pressure across the turbine [16]. But in the numerical model, the calculation of the pneumatic power depends on the instantaneous pressure change inside the chamber as seen in (16), which is derived from the thermodynamic part of the modelling. Therefore, at this stage of the modelling validation, the result may not be sufficient to make a pneumatic power comparison between the experimental and numerical results.

At the initial stage of the single rectangular fixed OWC device modelling, the numerical modelling provides a better understanding of the hydrodynamics and thermodynamics associated with the device in a regular wave. In the next step of development, the numerical model will be used to optimize device parameters which are influenced by the wave conditions. The developed numerical model is expected to be powerful enough that it could be an ideal tool for the optimal design and site selection with many numerical calculations. The developed numerical model can be extended in a straightforward manner to accommodate irregular wave cases which will be validated with subsequent experimental work.

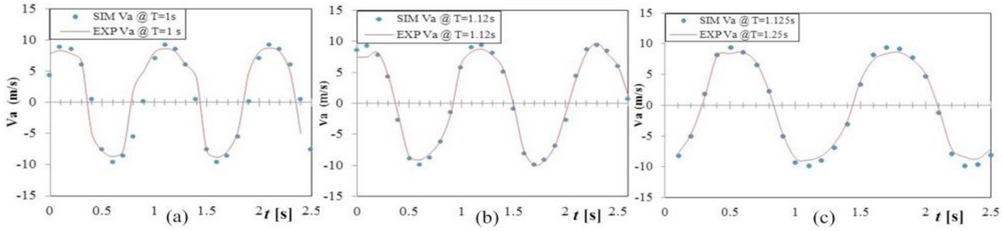

Fig. 5. Simulation and measured comparison of air flow velocity through the orifice aperture for a monochromatic wave with $T = 1$ s and orifice area (0.001034 m^2).

4. Conclusion

This paper assesses numerical models currently used for predicting a single OWC response in the time domain. The model combines hydrodynamic and thermodynamic system equations of a rigid piston model without power take-off; it is quantified via experimental data from a MC-OWC. Linear wave theory is assumed for the internal water surface level and the instantaneous pressure inside the chamber with regular waves conditions. The effects of the wave field diffraction, the vortex, and viscous effects are not considered. The numerical model shows acceptable agreement with experimental data with small-amplitude regular waves. Hence, it can be considered as a tool for the next step of device development, with irregular wave conditions, i.e., real wave conditions at a selected site.

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