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Numerical simulation of a submerged cylindrical wave energy converter

M. Anbarsooz*, M. Passandideh-Fard, M. Moghiman

Department of Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad 9177948944, Iran

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ABSTRACT

In this study, a numerical model based on the complete solution of the Navier–Stokes equations is proposed to predict the behavior of the submerged circular cylinder wave energy converter (WEC) subjected to highly nonlinear incident waves. The solution is obtained using a control volume approach in conjunction with the fast-fictitious-domain-method for treating the solid objects. To validate the model, the numerical results are compared with the available analytical and experimental data in various scenarios where good agreements are observed. First, the free vibrations of a solid object in different non-dimensional damping ratios and the free decay of a heaving circular cylinder on the free surface of a still water are simulated. Next, the wave energy absorption efficiency of a circular cylinder WEC calculated from the model is compared with that of the available experiments in similar conditions. The results show that tuning the converter based on the linear theory is not satisfactory when subjected to steep incident waves while the numerical wave tank (NWT) developed in the current study can be effectively employed in order to tune the converter in such conditions. The current NWT is able to predict the wave-body interactions as long as the turbulence phenomena are not important which covers a wide range of Reynolds and Keulegan-Carpenter numbers.

1. Introduction

The wave energy as a renewable energy has inspired numerous inventors and motivated many experimental and numerical investigations. Yet, several reviews have been published in this regard two of which are the book of McCormik [1] and a recent review paper by Falcao [2]. Although various types of wave energy converters (WECs) have been designed, no single technology has yet been recognized to be superior to the others.

The design of several WECs is based on the oscillatory motion of a submerged or floating part against a fixed reference. Depending on the water depth, different types of WECs might be more efficient in terms of energy absorption. The vertical force component of the waves are the main source of energy in the offshore WECs such as the floating buoys while near-shore devices, like bottom-hinged flaps, utilize the horizontal force component. A device where both the horizontal and vertical force components can be absorbed was first proposed by Evans [3]; this device includes a horizontally aligned cylinder that can move elliptically during the wave. He derived a linear theory for the performance of this class of wave energy absorbing bodies. The submerged cylinder exhibits a large efficiency (up to 100% theoretically) in a wide range of wave frequencies [3]. Dean [4] and Ogilvie, [5] using linear wave diffraction theory, showed that no energy is reflected from the cylinder whether it is fixed or freely buoyant. This fact is also valid for a case where the cylinder is constrained by springs and dampers in two orthogonal directions and the constants of spring and damper are the same in both directions [3]. Evans showed that for certain constants of the spring and damper corresponding to a given frequency, the transmitted wave would also be eliminated resulting in the complete absorption of the incident wave energy. Very recently, Heikkinen et al. [6] using the potential flow theory, investigated the effect of phase shift, cylinder radius, wave height and wave period on the efficiency of the submerged cylinder wave energy converter.

For wave energy applications, a good agreement has been reported experimentally in several studies (see for example [7]) between the results of the linear theory and those of the experiments in small ($H/L < 0.01$) to moderate wave steepness ($0.01 < H/L < 0.03$), where H and L being the wave height and length, respectively. However, for steep waves ($H/L > 0.03$) or in the wave conditions that excite resonances, due to non-linear and/or viscous effects, considerable discrepancies have been reported in the literature. Evans et al. [8] and Davis [9] demonstrated that the linear theory completely fails to predict the performance of the

* Corresponding author. Tel.: +98 511 8763304; fax: +98 511 8626541.
E-mail address: m.anbarsooz@gmail.com (M. Anbarsooz).

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submerged cylindrical wave energy absorbers for steep waves. This drawback of the linear theory is mainly due to its limiting assumptions namely assuming the flow to be linear and irrotational, and neglecting the viscosity effects.

A common practice to consider the effects of viscosity is to add a damping term similar to the drag term in the well-known Morison's equation [10]. This method has been employed by Davis [9] and Babarit et al. [11]. In this method, however, estimating the drag coefficient is a major problem. Although there are many experimental results available in the literature to determine the drag coefficient, this methodology leads to a poor prediction of the absorption efficiency [9] and considerable uncertainties in the results [11]. Therefore, considering a constant value for the drag coefficient for an elliptically moving cylinder will lead to unrealistic wave forces.

In this study, the behavior of a submerged cylinder WEC is simulated using the complete solution of the Navier–Stokes equations in conjunction with the fast fictitious domain method [12] for treating the solid objects. The numerical model is a modified version of the one previously developed by Mirzaii and Passandideh-Fard [13] for modeling fluid flows containing a free surface in presence of an arbitrary moving object. Using this numerical model, the wave forces on the submerged cylinder containing the viscous drag forces are calculated via solving the Navier–Stokes equations in each time step. The results of the proposed model show a good agreement with those of the experiments even for steep waves.

2. Mathematical model

2.1. Problem setup

The schematic of the computational domain shown in Fig. 1 is a rectangular numerical wave tank ($Lc \times Hc$) equipped with a flap-type wavemaker and two passive damping zones. A solid object representing the flap-type wavemaker is positioned at $x = Xp$ from the left, and the circular cylinder representing the wave absorber is initially placed at $x = Ls$ in the submergence depth S_d measured from the free surface. The cylinder is moored to the bottom of the tank via springs and dampers aligned at 45 degrees with respect to the x-axis.

The solid object representing the flap-type wavemaker is forced to move according to a prescribed harmonic motion in order to generate a desired wave. The domains of computations based on Fig. 1 are considered as: $Lc > 8L$, $Hc > 1.5d$, $Ld1 = 0.25$ m and $Ld2 > 2L$. More details on the wave generation methodology used in this study is given elsewhere [14]. The generated waves travel toward the submerged cylinder and force it to move; as a result, some parts of the wave energy are absorbed by the dampers.

2.2. Fluid flow

The governing equations for fluid flow are the Navier–Stokes equations in two-dimensional, Newtonian, incompressible and laminar flow:

$$\nabla \cdot \vec{V} = 0 \tag{1}$$

$$\frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V} = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\nabla \cdot \vec{\tau} + \vec{g} + \frac{1}{\rho}\vec{F}_{\rm b} \tag{2}$$

$$\vec{\tau} = \mu\left[\left(\nabla \vec{V}\right) + \left(\nabla \vec{V}\right)^T\right] \tag{3}$$

where $\vec{V}$ is the velocity vector, ρ the density, μ the dynamic viscosity, p the pressure, $\vec{\tau}$ the stress tensor and $\vec{F}_{\rm b}$ represents body forces acting on the fluid. The interface is advected using Volume-of-Fluid (VOF) method by means of a scalar field (F), the so-called liquid volume fraction, defined as:

$$F = \begin{cases} 0 & \text{in the gas phase} \\ 0 <, \ < 1 & \text{in the liquid} - \text{gas interface} \\ 1 & \text{in the liquid phase} \end{cases} \tag{4}$$

The discontinuity in F is a Lagrangian invariant, propagating according to:

$$\frac{{\rm d}F}{{\rm d}t} = \frac{\partial F}{\partial t} + \vec{V} \cdot \nabla F = 0 \tag{5}$$

2.3. Solid object treatment

As seen in Fig. 1, the solid objects that move within the computational domain are the flap-type wavemaker and the submerged circular cylinder which acts as the wave energy absorber. Both objects are modeled via the fast-fictitious-domain method [13] where the fluid flow equations are enforced everywhere in the computational domain including fluid and solid zones. This conceptual framework leads to a simple geometry and time independent computational domain which can be discretized by a structured and fixed grid mesh resulting in a considerable reduction of the required time for computations. There are several numerical approaches presented based on the fast-fictitious domain method such as those of Glowinski et al. [15,16], Patankar [17], Patankar et al. [18] and Sharma and Patankar [12]. The numerical method used in this study is a modified version of the Sharma and Patankar model [12] developed by Mirzaei and Passandideh-Fard

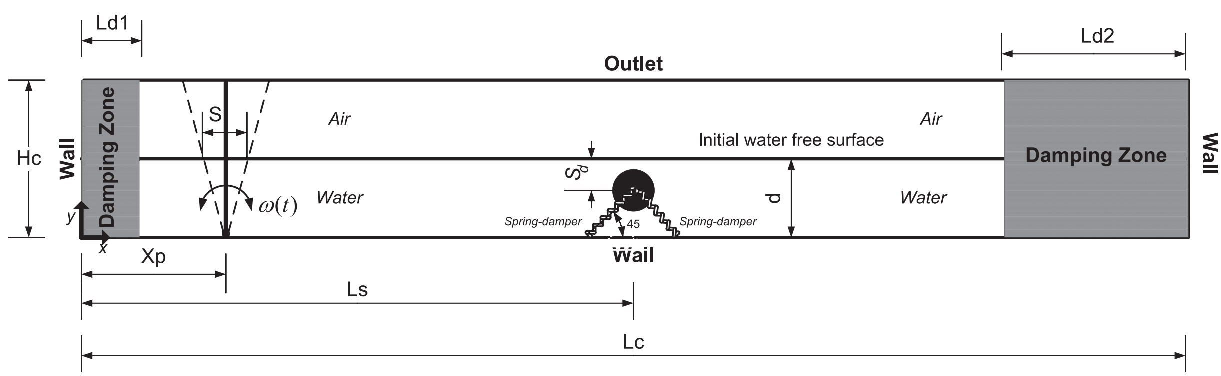

Fig. 1. Schematic of the computational domain.