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A nonlinear computational modeling of wave energy converters: A tethered point absorber and a bottom-hinged flap device

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ABSTRACT

A parallel computational tool based on solving the full two-dimensional Navier-Stokes equations was developed to predict the behavior of two types of wave energy converters (WECs). The two WECs, a point absorber and a submerged terminator are subjected to nonlinear incident waves which are generated by different types of wave makers in a water tank. The governing equations are solved on a regular structured grid to resolve the flow field. The solution is obtained using a control volume approach in conjunction with the immersed boundary method for treating the interactions of the solid objects with the fluid flow. The interaction between two fluid flow is determined by the Volume-of-fluid (VOF) method. A two-step projection method along with Multi-Processing (OpenMP) is employed to solve the flow equations. To validate the model, the numerical results are compared with the available numerical and experimental data in various scenarios where good agreements are observed. Two types of wave maker, a piston and a flap device, are considered to generate waves in a water tank. Then, two types of WECs, a tethered circular cylinder and a bottom-hinged flap device, are tested in the water tank to predict motion, power output and efficiency of these two devices with the steep incident wave.

1. Introduction

Sustainability and decreasing the dependence on fossil fuels have been investigated widely in last decades. The potential energy that can be extracted from the ocean waves is about 2000 TW-hr per year [1]. This amount of energy would be a large step towards becoming less dependent on fossil fuels for electricity. Wave Energy Converters (WECs) are considered as one possible option for sustainable electricity production recently.

In general, wave energy converters transform the movement of ocean waves into electricity. These systems consist of a primary interface, a power take-off system (PTO), and mooring in which the primary interface is the body of the WEC device which interacts with the waves. The wave-generated movements of the primary interface are transformed into electrical energy via the PTO devices, while the mooring restricts the free movements of the WEC [2].

Despite of wind turbines and solar panels, WEC devices has not been fully developed which causes many radically different ideas of how to extract usable energy from the ocean. These different designs of WECs can be classified based on the location and the method of capturing energy. Based on the location, the WECs are classified into three subdivisions: shoreline, near-shore, and offshore.

There are a complete review on different types of WEC devices in Refs. [2,3] which are also divided into several main groups which is shown in Fig. 1 [2].

The vast majority of recently proposed wave energy projects would use offshore floats, buoys or pitching devices [4]. Regarding the depth of water, different types of WECs might be more efficient in terms of energy absorption. The main source of energy in the offshore WECs is the vertical force component of the waves. However, horizontal force component of the wave is more effective in near-shore devices. Therefore, floating buoy and bottom hinged

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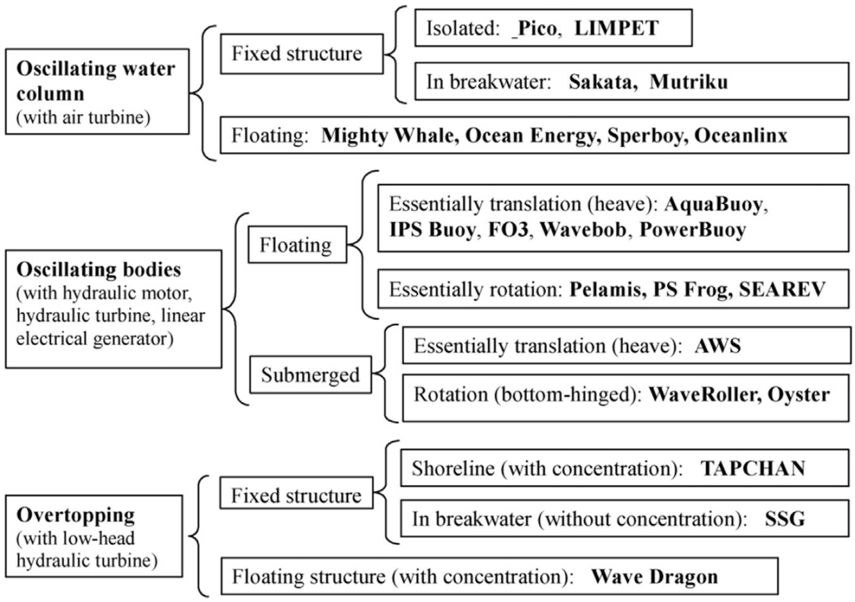

Fig. 1. Different types of WECs with Respective to Energy Capture Type.
Source: [2].

flap devices are more efficient in the offshore and near-shore, respectively [5] and our focus in this study is on the numerical investigation of these two types of WECs.

In the last decade, many researchers have used the analytical method to calculate the power output of point absorbers [2,6–8]. Moreover, Garnaud and Mei [9] presented an analytical solution to extract the wave energy by using infinite strips of buoys and a circular array. Although analytical methods are very efficient for providing a quick performance estimation, they are not accurate for some complex geometries. With the computer technology improvement, different numerical methods such as potential flow and finite element have been used during the technology's evolution to investigate WECs [10–12]. The required simulation time is increasing drastically by increasing the number of bodies and the dimensions of the domain. Evans [13] derived a linear theory to study the performance of wave energy absorbing bodies. In addition, Dean [14] and Ogilvie [15] by using linear wave diffraction theory presented that no energy is reflected from the cylinder whether it is fixed or freely buoyant. Heikkinen et al. [16] studied the efficiency of the submerged cylinder wave energy converter using the potential flow theory. Evans et al. [13] and Davis [17] have shown that the linear theory completely fails to predict the performance of the wave energy absorbers for steep waves. This drawback of the linear theory is because of its limiting assumptions which are assuming the flow to be linear, irrotational and inviscid. Also, by increasing the wave height, the inertia force are not the only crucial force and the drag force also has to be taken into account and it should be modeled [18].

Because of the limitation of the linear theory, Navier-Stokes equation-based method has often been used for studying the complex nonlinear waves interactions with bodies in ocean engineering problems [19–22]. Two types of approaches have been applied to track the free surface of fluids flow, tracking and interface-capturing methods. In tracking method, the free surface is considered as a sharp boundary which is updated with time [23]. This model has deficiency in modeling wave breaking and overtopping [24]. Marker-and-Cell (MAC) method [25], Volume-Of-Fluid (VOF) method [26], and the level set approach [27] are the most often used interface-capturing methods. Review of these methods and their application to wave hydrodynamics can be found in Refs. [28,29].

The immersed boundary and fictitious domain (FD) methods are the most popular methods in tracking moving solid objects in fluid flow. The main attributes of the fictitious domain (FD) method are that the solid object is treated as a fictitious fluid, and the governing equations of fluid flow are solved in the entire domain, including inside the solid object. The solid velocity is then corrected to impose the solid rigidity condition. The correction leads to a fluid-solid interaction force. In the immersed boundary method a distribution function is used to interpolate the fluid velocity from a Eulerian grid onto the Lagrangian markers and to spread the forcing term computed at the Lagrangian markers onto the surrounding Eulerian nodes. The solid boundary interacts with the fluid by means of local body forces applied at the position of the solid points to the fluid. This body force imposes the kinematic constraint that the velocity at each of these solid point is coupled to the fluid velocity at that point. The introduction of these body forces has become the basic idea behind several fluid-solid interaction methods [30]. The FD and the immersed boundary methods have been used to capture the interactions of solids with single and two-phase fluid flows as shown in Refs. [31–35]. Moreover, a few studies

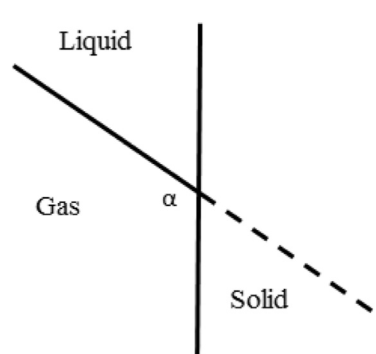

Fig. 2. Contact angle, α, on the three-phase intersection point. The dashed line shows the extension of the VOF function inside the solid.