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Towards simulating floating offshore oscillating water column converters with Smoothed Particle Hydrodynamics

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ABSTRACT

The mesh-free code DualSPHysics is applied to simulate the interaction between sea waves and an Oscillating Water Column device (OWC). In this work, capabilities and limitations of DualSPHysics are shown in simulating OWCs. On the one hand, the new capabilities of DualSPHysics are shown by simulating the effect of mooring systems on a floating offshore OWC. On the other hand, simulations only consider a single-phase (water) so that the full OWC behaviour is partially reproduced, i.e. air pressure fluctuations are not modelled. The model was first validated with one laboratory test that consists of a fixed OWC with an open chamber. Next, water surface oscillations inside the chamber of a real OWC (located in Mutriku, Spain) have been predicted using the prevalent wave conditions observed in the area. Finally, the capabilities of DualSPHysics were demonstrated by simulating an offshore OWC moored to the seabed.

1. Introduction

Significant research is being conducted into renewable resources due to the increasing demand for energy and to the uncertainty to climate change. Wave energy is in fact one of the most available and cleanest renewable energy sources. Wave energy has the advantage of being considered as the most concentrated and least variable form of renewable energy. Previous research (Drew et al., 2009) has shown that wave power devices can generate power up to 90 per cent of the time, compared to 25 per cent for solar and wind devices.

There are several projects worldwide regarding wave energy, but the potential of this source is still not fully investigated. At present, different wave energy concepts are being investigated by companies and academic research groups. Oscillating water column (OWC) devices consist of a partially submerged reservoir with water open to the sea and a chamber of trapped air. The ocean waves change the water level inside the tank, which compresses and decompresses the air inside the chamber. This trapped air is allowed to flow to and from the atmosphere via a turbine whose rotation is used to generate electricity. The shoreline OWC's are currently the most sensible designs since they do not have any moving parts in the water, leading to easier maintenance works. There are several full-scale prototypes of OWC around the world such as:

i) LIMPET plant near the Scottish island of Islay with a total installed capacity of 500 kW (Heath et al., 2000);
ii) PICO plant in Azores (Portugal) for a power of 400 kW (Falcão, 2000);
iii) MUTRIKU plant in Spain that consists of 16 chambers of 18.5 kW each (296 kW in total) and covers the energy consumption of 1000 population in 1 year (Torre-Enciso et al., 2009).

However, sea waves propagating towards the coast suffer from attenuation, refraction and shoaling as they approach the shoreline (Goda, 2010). So that, some of the wave power is lost and offshore floating OWCs can be a better option. Some examples of floating OWC devices at an advanced stage of development are the OE Buoy and the Oceanlinx Mk3. The OE Buoy is developed by Ocean Energy company and has been deployed in Atlantic waters and demonstrated the ability to generate power and survive in the most extreme conditions of the ocean (http://oceanenergy.ie/platform/). A 1/4th scale model of the OE Buoy device was tested in the Galway Bay (Ireland) (Thiebaut et al., 2011) and the Oceanlinx Mk3 prototype was tested in the coast of Port Kembla (Australia), in 2010 (Falcão, 2010).

More complete reviews about OWC can be found in Heath (2012) and Falcão and Henriques (2016) and the linear interactions between ocean waves and oscillating systems are properly described in Falnes (2002).

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Three important steps can be considered in the design of a wave energy converter; numerical modelling, model scale tests in wave tanks and testing *in situ*. Many designs have been developed and tested through numerical and physical modelling (i.e. wave tanks) at a research stage and only a small number of devices has been tested in the ocean. In fact, these prototypes are generally built by companies or thanks to private investors. Laboratory experiments on an axisymmetric floating OWC in a wave channel were reported by Whittaker and McPeake (1985). Morris-Thomas et al. (2007) carried out experiments to determine the influence of wall thickness, shape of the front wall and draught of the front wall for various wave parameters on the hydrodynamic efficiency of an OWC device. More recently, López et al. (2015) presented physical model tests that allowed to quantify the effects of the damping coefficient, wave conditions and tidal level on the performance of an OWC chamber. Nevertheless, there are insufficient experimental databases with OWC devices and, in most of the cases, the variables of interest (chamber free-surface oscillation, air pressure variation and air flux between the chamber and the atmosphere) have not been measured jointly. Thus, numerical models are a suitable and necessary tool to contribute in OWCs design once models are properly validated against experimental data. The main advantage of the numerical simulation is the capability to simulate complex scenarios and provide physical data that can be difficult, or even impossible, to measure in real or scale models. Despite of the accuracy of the numerical models, these cannot replace the construction of scale models, but they can reduce significantly the number of physical tests. This leads to important savings since the construction of physical models is very expensive and time consuming.

The hydrodynamic interaction between WECs and ocean waves is a complex non-linear process that has being numerically studied using different approaches. McCormick (1974, 1976) developed the first numerical models on OWC devices, based on empirical values for the hydrodynamic coefficients. Evans (1978) developed a theoretical model for a fixed OWC device considering the internal free surface as a weightless piston. Later the models of Evans (1982) and Sarmento and Falcão (1985) considered the deformation of the free surface through the application of the oscillating surface-pressure distribution condition. The numerical models to simulate OWC that can be found in the literature are here summarised in two groups: i) time domain models based on linear water wave theory, and ii) CFD codes based on the integration of the Navier-Stokes equations (meshbased and meshless). Table 1 summarises the main features of the different approaches that will be presented in detail.

In the first group, time-domain models based on frequency domain data are usually built upon the Cummins equation (Cummis, 1962). The Boundary Element Method (BEM) is used to solve the Laplace equation for the velocity potential, which assumes the flow is inviscid, incompressible, and irrotational. BEM was originally formulated for analysing the motions of ships and assumes that all the hydrodynamic forces on a floating body (i.e. wave energy converters) can be modelled using a set of hydrodynamics coefficients. With information of incoming waves as input, BEM computes added masses, the radiation damping coefficients and excitation force coefficients. The movements of the structure (heave, pitch and roll) are obtained from the solution of the frequency-domain or time-domain equations and require information on the sea state and on the PTO (power take-off system). The main advantage of these models is that the codes are very fast and efficient. The problem is that assuming a linear behaviour, WECs cannot be modelled in energetic sea states or close to resonance. The main limitations derive from the small wave amplitude and small motion amplitude assumptions and the incapability to account for real fluid (viscous) effects (boundary layers, turbulence, vortex shedding).

The approach of Evans (1982) was later applied to particular OWC geometries, using BEM (Brito-Melo et al., 2001; Delauré and Lewis, 2003; Josset and Clément, 2007). Alves et al. (2010) performed a numerical analysis of an axisymmetric floating OWC using a boundary element method to account for the hydrodynamic interferences between the buoy (a cylindrical floater with a tail tube) and the OWC. Iturrioz et al. (2014) validated their own time domain model with experimental data of a fixed detached OWC. Some software examples are the commercial WAMIT (WAMIT, 2012), WADAM (DNV, 2008) or WaveDyn and the open-source codes Nemoh developed by LHEEA (Babarit and Delhommeau, 2015) and WEC-SIM developed by NREL/Sandia (Lawson et al., 2015; Combourieu et al., 2015) at http://wec-sim.github.io/WEC-Sim/.

The second main group consists of those models based on the Reynolds Averaged Navier–Stokes (RANS) equations and presents several advantages, not only for solving the velocity field in the whole domain but also for overcoming the limitations of nonlinearity. Thereby, CFD models that approximate Navier–Stokes equations are considered one of the best numerical tools to study the hydrodynamic interaction between waves and WECs. Particularly powerful within this group are those models that include the Volume Of Fluid (VOF) method to capture the movements of the free surface. These models can simulate viscous losses and non-linearities that occur in the interaction between the device (fixed or floating) and the wave train, so that, violent flows with large amplitudes can now be simulated. However, they need an extra algorithm to track free-surface and meshing complex geometries or floating bodies is a hard task. Actually, due to computational requirements, the numerical integration of the RANS equations to model OWC converters was applied, in many cases in the literature, to two-dimensional geometries. Paixão Conde and Gato (2008) carried out a numerical study of an OWC with the commercial CFD code Fluent (also based on finite volumes), investigating the flow distribution in the chamber and the properties of the air-jet impinging on the free-surface. Teixeira et al. (2013) analysed the chamber geometry (front wall depth, chamber length and chamber height) and turbine characteristic relation by means of Fluinco model (a semi-implicit Taylor-Galerkin method) where a comparison between Fluinco and Fluent models was also carried out, obtaining a good agreement. There are many other works using two-phases RANS and VOF models for OWC modelling, but few of them show validation with experimental data. Zhang et al. (2012) developed a 2D-RANS model to study wave interaction with a semi-submerged OWC chamber and analysed its impact on the energy efficiency. The validation of the model was carried out using the experiments presented by Morris-Thomas et al. (2007). Some recent works also present the validation of the STAR-CCM + model in López et al. (2014) where a RANS-VOF numerical model is used to study the OWC performances for different wave conditions and damping values. López and Iglesias (2014) applied artificial neural networks (ANNs) to predict the pneumatic efficiency of OWC converters. The validation of the open-source code REEF3D (https://reef3d.wordpress.com/) is presented in Kamath et al. (2015a). REEF3D is also used in Kamath et al. (2015b) where the PTO damping on the chamber is represented using a linear pressure drop law with the permeability coefficient derived from Darcy's equation for flow through porous media.

Table 1
Numerical models for solving the dynamics involved in WEC analysis.

	Time domain models	CFD models	
		Meshbased CFD	Meshless CFD
Equations	Cummis equation + Linearised hydrodynamic coeffs.	Navier Stokes	Navier Stokes
Method	Boundary Element Method	Finite Volume	Smoothed Particle Hydrodynamics
Viscosity	Inviscid	Viscous	Viscous
Linearity	Linear	Non-linear	Non-linear
Suited for	Low amplitude motions Small oscillations	Viscous losses	Large deformations + Rapidly moving geometries
Efficiency	Fast and efficient	Time consuming + Mesh generation	Very time consuming
Codes	WAMIT, WADAM. AquaDyn, WaveDyn WEC-Sim, Nemoh	VOF, OpenFoam, IH-Foam, Fluent, Fluinco, REEF3D	DualSPHysics

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