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Numerical hydrodynamic analysis of an offshore stationary–floating oscillating water column–wave energy converter using CFD

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Abstract

Offshore oscillating water columns (OWC) represent one of the most promising forms of wave energy converters. The hydrodynamic performance of such converters heavily depends on their interactions with ocean waves; therefore, understanding these interactions is essential. In this paper, a fully nonlinear 2D computational fluid dynamics (CFD) model based on RANS equations and VOF surface capturing scheme is implemented to carry out wave energy balance analyses for an offshore OWC. The numerical model is well validated against published physical measurements including; chamber differential air pressure, chamber water level oscillation and vertical velocity, overall wave energy extraction efficiency, reflected and transmitted waves, velocity and vorticity fields (PIV measurements). Following the successful validation work, an extensive campaign of numerical tests is performed to quantify the relevance of three design parameters, namely incoming wavelength, wave height and turbine damping to the device hydrodynamic performance and wave energy conversion process. All of the three investigated parameters show important effects on the wave–pneumatic energy conversion chain. In addition, the flow field around the chamber's front wall indicates areas of energy losses by stronger vortices generation than the rear wall.

Keywords: Offshore oscillating water column; OWC; Wave energy; Energy balance; Numerical wave tank

1. Introduction

Wave energy is one of the most promising renewable energy resources and research is being conducted worldwide. There is a large number of invented techniques for wave energy conversion which can be categorised by deployment location (shoreline, nearshore and offshore), type (attenuator, point absorber and terminator) and mode of operation (submerged pressure differential, oscillating wave surge converter, oscillating water column and overtopping device) (Drew et al., 2009).

The Oscillating Water Column (OWC) is a wave energy extraction device that is based on wave to air energy conversion by driving an oscillating column in a chamber open to the sea. The air energy is extracted by means of a bi–directional air turbine connected to the chamber. As the water level oscillates up and down inside the chamber, the air inside it is compressed and decompressed, respectively. In turn, this process generates mechanical energy through a reversible flow between the atmosphere and the chamber utilizing an air turbine that rotates in the same direction regardless of the airflow direction. Different from other Wave Energy Converters (WEC), OWCs are not only one of the simplest devices from an operational point of view, but also having no moving parts underwater provides lesser and easier maintenance works. OWCs can be deployed as fixed structures at the shoreline or nearshore, or integrated in breakwaters and floating structures (Falcão and Henriques, 2015).

Investigating the hydrodynamic performance of OWCs has been studied analytically, experimentally, numerically or a combination of the aforementioned. A theoretical model of the

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hydrodynamics for a fixed OWC device was developed by Evans (1978). Ignoring the spatial variation, Evans assumed a rigid weightless piston motion for the chamber's internal free surface of a small width relative to the incident wavelength, which allowed the application of the oscillating body theory. Falcão and Sarmento (1980), Evans (1982) and Falnes and McIver (1985) improved the rigid−body approach of an OWC via allowing the increase in pressure at the free surface as well as providing the possibility of a non−plane surface.

With the aim of validating the oscillating surface pressure theory proposed by Sarmento and Falcão (1985) in OWCs, Sarmento (1992) conducted a set of wave flume experiments with regular waves of very small steepness under linear, as well as quadratic, power take−off (PTO) simulated by either filters or orifice plate, accordingly. Hong Hong et al. (2007) performed a 2D experiment concentrating on the effects of several shape parameters of OWC chamber in wave energy absorbing capability. Morris-Thomas et al. (2007) performed experiments in a wave flume to investigate the influence of the chamber's front wall thickness, shape and draught under various wave parameters on the hydrodynamic efficiency of a shore−based OWC device.

Generally, numerical models can be divided into two categories; the first category is based on applying potential flow theory, which is usually solved with a boundary element method (BEM). Extensive review of potential flow models can be found in Baudry et al. (2013). The second category, which is applied in the present study, is based on Reynolds−averaged Navier−Stokes (RANS) equations, which provides more advantages in overcoming the potential flow weaknesses in handling problems that involve strong nonlinearity, dispersion, wave breaking, complex viscous, turbulence and vortex shedding. This method is widely used by several researchers; examples that are most relevant to the present study include Zhang et al. (2012) who developed, validated and studied the impact the geometrical parameters have on a shore−based OWC efficiency curve using a 2D two−phase numerical wave tank based on a level−set immersed boundary method. They reported a reasonable agreement with experimental data measured by Morris-Thomas et al. (2007) for the device hydrodynamic efficiency with a slight over−prediction attributed to the complex pressure changes in the chamber around resonance. Additional parameters such as pressure variation, free surface elevation inside the chamber and flow field were presented and discussed, but without comparison to experimental data. Teixeira et al. (2013) implemented a numerical model (Fluinco) based on the two−step semi−implicit Taylor−Galerkin method to simulate a fixed OWC device subjected to regular waves. After validating their model against numerical results from the commercial CFD code Fluent, they investigated the effects of the chamber geometry including the front wall depth, chamber length, chamber height and the turbine characteristic relation that provide the best device performance. Luo et al. (2014) implemented a 2D numerical model using a commercial CFD code (Fluent) to investigate the effect of wave nonlinearity on the capture efficiency of an onshore OWC device. López et al. (2014, 2016) studied the importance of different turbine damping coefficients on the performance of an onshore OWC device under regular and irregular waves to determine the optimum turbine−induced damping on an OWC device using a 2D commercial CFD model (Star−CCM+). Kamath et al. (2015a, 2015b) utilized a 2D open−source CFD model (REEF3D) to simulate and study the interaction of a fixed shore−based OWC with regular waves of different wavelengths and steepness, and also investigated the response of the OWC under different damping values from the PTO device.

Quantifying the energy losses inside OWCs has not been studied extensively in comparison with the considerable research effort focused on the overall hydrodynamic performance and geometry optimization of onshore OWCs. Always in such research, there is a part of the incoming wave energy that is assumed to be lost inside the OWC system; however, only a few researchers have paid more attention to either visualizing and/or quantifying such losses. Only via visualizing the flow behaviour in a shoreline OWC, Müller and Whittaker (1995) highlighted different energy loss mechanisms. Tseng et al. (2000) experimentally estimated about 33%−68% energy losses throughout the energy conversion chain for a multi−resonant cylindrical caisson. Similarly, Mendes and Monteiro (2007) carried out a series of wave tank experiments on a shoreline OWC under regular waves. In addition to studying the energy conversion chain and estimating the energy losses, they visualized the flow inside the OWC using a sequence of video−frames to discover the energy dissipation physics.

Furthermore, by utilizing advanced measurement techniques such as particle imaging velocimetry (PIV), a detailed flow field picture can be obtained. For instance, using PIV, Morrison (1995) calculated the kinetic energy and viscous dissipation rates in a shore−based OWC. Graw et al. (2000) studied the impact of an onshore OWC underwater geometry such as the front lip shape and its inclination on the energy losses in the vicinity of the lip over four wave frequencies. They concluded that at low frequencies with the cornered lip shape, the mean energy losses over one cycle (mean dissipation divided by the mean power) may be as much as 15%. Within the wave energy balance framework, Fleming et al. (2011, 2012a, 2012b and 2013) utilized flow field measurements using PIV in a forward facing bent duct OWC with a phase−averaging technique to perform detailed energy balance analyses considering different energy sources, stores and sinks components. López et al. (2015) applied Reynolds decomposition technique to estimate the turbulent kinetic energy in a shore−based OWC by resolving the velocity fluctuations from PIV measurement. Using this methodology, they investigated the relevance of different wave conditions, PTO pneumatic damping and change in tidal level on the OWC hydrodynamic performance. With respect to numerical modelling, Elhanafi et al. (2016b) developed a 2D numerical model based on RANS−VOF with validation against experimental results including PIV data. Building on the achieved good agreement, they applied their model to further investigate the impact of increasing the incident wave amplitude and

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