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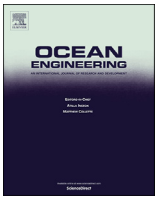

Experimental and analytical investigation on chamber water surface fluctuations and motion behaviours of water column type wave energy converter

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ABSTRACT

One of the most promising wave energy converter type is Oscillating Water Column (OWC) system. Fluctuation amounts and the motion behavior of the water column inside the chamber are very important parameters effecting the energy extraction. Therefore, predicting these parameters with respect to varying wave characteristics and geometric design parameters is of great importance. In this study, physical experiments are conducted for a bottom-fixed OWC system with seven different sizes of opening heights under various regular wave series. Average fluctuations inside the chamber are measured. It is found that there is a critical relative opening height ratio (α) that makes the fluctuations maximum regardless of wave parameters used. Exponential and linear relationships are found between average fluctuations and dimensionless parameters 'dimensionless wave frequency' and 'captured wavelength' defined, respectively. Mathematical models are developed to predict water column fluctuations under varying relative opening heights and wave parameters. The results of mathematical models indicated good aggrement with experimental data. Also chamber water surface profiles are observed and related to defined dimensionless wave parameters. Another factor (named as excessive harmful energy) is determined which also induces sloshing motion inside the chamber after the critical ratio value α is exceeded. It is found that under all wave series, the highest relative average column water surface fluctuations occur at relative opening height α is equal to 0.67 which is a unique value. It can be concluded that mathematical models can be used to estimate water column fluctuations from relative opening height and wave parameter data in the chamber.

1. Introduction

It is a well known fact that, replacing our current energy sources with renewable ones is very crucial for our future (https, 2016). While energy demand is increasing by growing population and developments in technology, with the realization that conventional energy sources are still excessive and more accessible than others, it is not an easy task (www.conserve-energy-futur, 2017). But unlimited and untapped ocean wave energy that has relatively greater power intensity compared to solar and wind energy is one of the auxiliaries which may help humanity achieve their responsibility for future generations. Efforts have already been ended up more than 1000 wave energy extraction devices and techniques patented in the world (Mc Cormick, 1981).

OWC converter system is the most promising and studied one with its simplicity, adoptability and its well acceptancy. It consists of a partially submerged hollow chamber with an opening beneath the water level towards the sea that has air trapped above it and a narrow duct at the top or rear of the device interacting with only air. Wave forces acting on the inlet of the converter system causes the water column inside the chamber act on a reciprocating manner which, in turn generates the pressure variations above it. Pressure differences inside and outside the converter system forces air to flow in and out with high velocities. Then the generated pneumatic power can be converted again to electric power by a bidirectional turbine attached to the device that turns in the same way independent of airflow direction. A navy officer of Japan Yoshio Masuda who is one of the first pioneers in the field, used wave energy to power navigation buoys oscillating under random waves with a turbine attached. This system is named as oscillating water column afterwards (Falcao and Henriques, 2016). Lots of efforts have been conducted by studying them analytically, numerically and experimentally since OWCs are one of the promising and major type of wave energy convertors. This accumulation of knowledge from the performed studies conveyed us to the stage of deploying full-scale prototypes such as bottom fixed 400 KW Pico Plant on the Island of Pico, Azores, Portugal, 500 KW LIMPET OWC

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plant on the Island of Islay, Scotland, UK, Oceanlinx OWC, Port Kembla, Australia, a breakwater integrated OWC at the port of Mutriku, in Northern Spain. It is reported that in the Limpet OWC system, more than sixty thousand kilowatts has been generated to the national energy grid (Heath, 2012).

First attempts of theoretical analysis for OWC system were conducted by McCormic on wave energy conversion buoys (McCormick, 1974, 1976). Evans (1978) used a rigid body model and studied the hydrodynamics of a fixed OWC system theoretically ignoring the spatial variation of the free surface in the chamber. He assumed the free surface of the chamber as a rigid weightless piston and a small width relative to the incident wave length. Under these assumptions oscillating body theory was able to be used. This analysis further developed by Evans (1982), Falnes and Mclver (Falnes and McIver, 1985) by allowing pressure increase at the free surface which enables the possibility of deformable surface (non-plane surface). Sarmento and Falcao (1985) used linear wave theory to develop a two-dimensional OWC analytical model with both linear and non-linear power take off (PTO) systems. Optimal pneumatic damping required for the compression of air for high efficiency is also studied. Evans-Porter (Evans and Porter, 1995) considered a two-dimensional simple model of an OWC system and their theoretical studies to calculate the hydrodynamic characteristics of the system. They developed an approach using Galerking Method. They claimed that immersion depth of the front wall and chamber length are the main parameters affecting the hydrodynamic efficiency. Sarmento (1992) conducted wave experiments with regular waves which have low steepness and showed the importance of pressure distribution in the chamber for the optimal efficiency of OWC system.

Morris-Thomas et al. (2007) studied the hydrodynamic efficiency of a shore based OWC system experimentally under progressive plane waves suitable to linear wave theory. They focused on studying the parameters front wall draught, thickness and aperture design of the submerged front wall under various wave parameters which found that they are affecting the shape and bandwidth of the hydrodynamic efficiency curve. This experimental study is also one of the mostly used one for validation of numerical results.

Wang et al. (2002) experimentally and numerically studied the hydrodynamic performance of a shoreline-mounted OWC system by using boundary element method. After validating their model with the experiments conducted under regular wave conditions with different bottom slopes, they investigated effects of bottom slope and water depth. Hydrodynamic efficiency of an OWC system was investigated numerically by Zhang et al. (2012) using a two-phase level set immersed boundary method under regular waves with turbine damping. They compared their study with the two-dimensional theory of Evans-Porter (Evans and Porter, 1995) and Morris-Thomas et al. (2007) and they showed that hydrodynamic efficiency results agree with physical parameters more than inviscid linear theory. They found that when the orifice dimension increases it causes a pressure drop in the chamber which in turn decreases the hydrodynamic efficiency.

Kamath et al. (Kamath et al., 2015) investigated the hydrodynamics of an OWC including the free surface elevation under incident wave series using two dimensional numerical wave tank. They found that there is a strong relationship between incident wave amplitude and free surface motion and, waves having larger wavelength and amplitude generate larger chamber pressure.

Ning et al. (2016) performed an experimental study to research the hydrodynamic efficiency of a fixed OWC structure. Miscellaneous geometric parameters were tested under various wave parameters. The ratio of the exit area to chamber area was found to be 0.66% for optimal efficiency.

An experimental study was performed by Chang et al. (2016) for investigation of OWC systems geometrical design including back plate angle, fence plate and open wide parameters to optimize the maximum amplification of wave energy. They concluded that chamber geometry especially back plate angle optimization is very significant for the wave amplification factor of the OWC system.

Mahnamfar et al (Mahnamfar) made an investigation for the optimization of an OWC system by using both physical and numerical models. They changed the geometric parameters of an OWC structure with an angular front plate and tested at several circumstances. Experimental model results were compared with the numerical model results. Nash-Sutcliffe coefficient of Efficiency (NSE) parameter was used as performance evaluation criteria and the NSE values found to be 0.97.

Hydrodynamic efficiency of the OWC system is studied by Boulai and Larbi (Bouali and Larbi, 2013) in terms of chamber geometry, dimensions and their effects. Further, the geometry is optimized to maximize the efficiency.

Despite the progress been made, it is not a straightforward task to figure out a unique design and commercialize it globally because the wave climate is not same everywhere and wave-body and wave-air interactions are very complex to be solved mathematically. Wave parameters are maybe the most important factor for extracting wave energy in a most efficient way and at a great extent. Also, the geometric parameters should be justified for the prevalent wave climate (Mahnamfar). Due to the complexity of the energy extraction processes it is obvious that a unique design for all wave climates even for a particular wave characteristic could have not been invented so far. More investigations and studies including every design parameter with different wave characteristics must be in progress. Experimental studies are in the minority among analytical and numerical ones. Their expensive, time-consuming and labor force requiring nature makes them harder to conduct. Also, they are needed for verification of analytical and numerical studies.

To the best of our knowledge, there is not an experimental study concentrating solely on the water column fluctuations with respect to various opening heights and different wave parameters in detail. Also, any simple and practical mathematical model does not exist to predict the water column fluctuations in the chamber from opening heights and wave parameters. Even though surface profiles are defined in terms of efficient energy extraction in the literature, there is not a precise, enough observation to clarify two distinct surface profile types which are piston and sloshing types with respect to wave parameters and opening heights. Furthermore, the data of water column surface fluctuations are mostly measured from a single point inside the chamber for the former experimental studies (He et al., 2013). In this study three wave gages were located in the chamber to measure the average water column surface fluctuations. This is important because chamber water column surface profile across the cross section is often not planar and measurements performed from a single location may not represent the whole surface fluctuations appropriately.

The objectives of this study are:

I To investigate the effect of various opening heights of OWC system on the chamber water column surface fluctuations under various regular wave conditions by physical models.
II To investigate the effect of various wave parameters on the surface fluctuations of the chamber for different opening heights.
III To investigate chamber water column surface profile behaviors depending on various opening heights and wave parameters.
IV To develop mathematical models to predict water column fluctuations inside the chamber from opening height and wave parameter values.
V To evaluate physical experimental model results with mathematical model results.

2. Material and methods

2.1. Experimental study

The physical experiments were conducted in the Hydraulics Laboratory of Istanbul Technical University. A 22 m long, 1 m high and 1 m wide wave flume was used for the experiments. To absorb the outgoing wave energy for avoiding reflection from the back wall of the wave flume, a sloped (1:4) porous type beach was constructed at the end. Sides of the