Ocean Engineering 131 (2017) 162–173

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Sequential optimization and performance prediction of an oscillating water column wave energy converter

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ARTICLE INFO

Keywords:
Wave energy converter
Oscillating water column
Numerical wave tank
Hydrodynamic efficiency
Sequential optimization

ABSTRACT

This paper presents a sequential optimization procedure and a performance prediction of an Oscillating Water Column (OWC). The effects of the Power Take-off (PTO) model, the geometry, and the wave conditions on the device performance are investigated. Numerical simulation tests are carried out within a Numerical Wave Tank (NWT), where nonlinear higher-order Stokes regular wave's velocity profile is continuously applied at the tank inlet. The wave propagation is predicted according to Reynolds Averaged Navier-Stokes and two-phase homogeneous Volume of Fluid model. By considering an OWC with a specific configuration, the developed optimization procedure consists in determining the optimal parameters set in a sequential manner (i.e. determine the 1st optimal parameter, keep it fix, optimize the 2nd, and so on…). A recurrent procedure is used to check the non-interactivity between the various tuned parameters and consequently the design optimality. The obtained results show that for an OWC there is a single optimal operating point that depends on the PTO damping, the thickness of the OWC front wall and its immersion depth, and the wave conditions. It is also shown that the use of a performance prediction based on rational- polynomial functions yields an accurate approximation of the optimal operating point.

1. Introduction

One of the very important wave energy converters (WECs) is the oscillating water column which has had one of the longest development periods among WECs (Zabihian and Fung, 2011). An OWC basically consists of a special chamber, which collects and converts incident waves to pneumatic energy; and a PTO system, which transforms this energy to useful mechanical work. The chamber inlet (front wall) is partially submerged, in order to allow the incident waves to penetrate into the chamber, and the PTO is usually located on the lateral (rear) or upper wall (see Fig. 1). The operating principle relies on the inner water free surface oscillations, which cause the air column compression and expansion at the same time as the inner water level rises and falls. The air flow thereby created through an orifice can drive a turbine connected to a generator. The most commonly used turbines for OWCs are Wells turbine, self-rectifying impulse turbine, and savonius rotor (Bouhrim and El Marjani, 2014; João, 2008).

Over the last number of decades, many efforts including analytical, experimental, and numerical investigations have been made in order to study the OWC performance. Evans (1982) was first to develop general expressions for the mean power absorbed by an arbitrary system of pressure distributions. Afterward, Sarmento and Falcão (1985) developed a two-dimensional analysis for an OWC of arbitrary constant depth, where both linear and nonlinear PTO models were considered. Within linear theory, Malmo and Reitan (1985) studied a wave-power absorption by an OWC for different boundary conditions regarding the region between the absorber and the channel walls. In this research, a particular attention was given to the effect of the front wall immersion depth. As previously, on the basis of wave linear theory, Evans and Porter (1995) developed an analytical method for computing hydrodynamic coefficients associated with a pressure distribution model of a simple OWC device. Still in the context of linear theory, Şentürk and Özdamar (2012) presented a theoretical model for an OWC where a two-dimensional problem was formulated and solved using matched eigenfunction expansions and a Galerkin approximation. Regarding the device performance, the study showed that it is possible to improve the efficiency of an OWC, with a surface piercing type front wall having the same resonant frequency, by selecting suitably the geometrical settings.

On the other hand, many authors have focused their efforts on experimental studies. Sarmento (1992) performed a validation of the oscillating surface pressure theory, developed by Sarmento and Falcão (1985), by a set of wave flume experiments on OWC devices. His tests

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http://dx.doi.org/10.1016/j.oceaneng.2017.01.004
Received 29 May 2015; Received in revised form 5 November 2016; Accepted 6 January 2017

Nomenclature

a	wave amplitude
b	OWC chamber size
c	OWC front wall width
C	wave celerity
c_{air}	air compressibility
C_{cfl}	Courant number
e	OWC front wall immersion depth
E_{in}	instantaneous incident wave energy flux
f	volume fraction
g	gravitational acceleration
h	water depth
H	wave height
k	wave number
L	NWT length
p	pressure
p_c	average air pressure in the OWC chamber
P_{in}	incident power
P_n, Q_m	polynomial functions of degrees m, n respectively
P_{out}	output power
q	volumetric flow
t	time
T	wave period
u	Velocity x-component
V	velocity vector
w	Velocity z-component
x	horizontal direction
y	normal direction
z	vertical direction
Δp	pressure drop
Δp_m	average pressure drop
Δx, Δy, Δz	grid sizes in x, y, and z directions respectively
β	damping coefficient
ε	OWC efficiency
η	water surface elevation
κ	length scale
λ	wave length
μ	dynamic viscosity
θ	slop bottom angle
ρ	density
ω	wave frequency

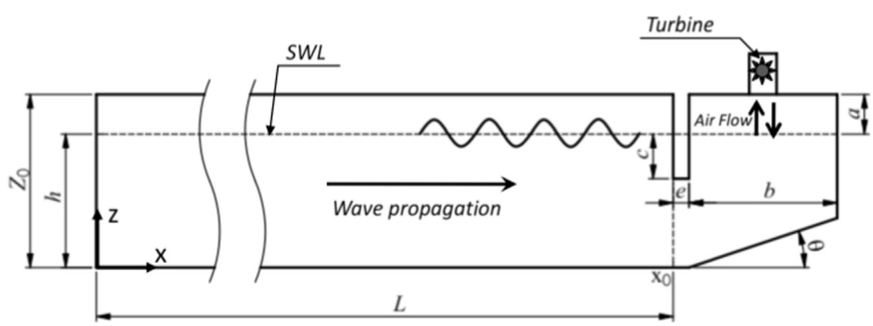

Fig. 1. Schematic representation of a simple OWC.

included specially the effects of increasing the OWC immersion depth. Morris-Thomas et al. (2007) performed a series of experiments on an OWC to analyze energy efficiencies for PTO. In their study, the effects of the front wall immersion depth, the thickness and the aperture shape of the device are also examined. A hydrodynamic efficiency peak of about 70% is observed through these experiments. By using pressure and velocity measurements, Ram et al. (2010) studied the air flow in an experimental OWC set. Experiments were performed by varying the water depth and the wave frequency. It was found that the air velocity in the turbine chamber during the upward motion of water in the column is always larger than that during the downward motion. Good agreement is observed between the oscillating pressures in the air chamber and the fluctuating velocities recorded with Particle Image Velocimetry (PIV). Liu et al. (2011b) conducted an experimental study on an OWC caisson breakwater. It was found that the power conversion efficiency of this system varies between 2.52% and 28.29%, and the device can work well in sea area with wave height larger than 1.5 m and period of time longer than 6 s Hsieh et al. (2012) designed and analyzed a two chamber OWC for a specific site in Taiwan. They performed experiments on a scaled-down model in a wave tank, and demonstrated that the two chamber design can enhance the device performance. Recently, Gomes et al. (2012) have tested a small scale spar-buoy OWC in a flume under regular waves. The viscous effects neglected in the mathematical model were found to be important in their small scale model. More recently, He et al. (2013) proposed a floating breakwater with asymmetric chambers to increase the amplitude of the oscillating air pressure inside chambers. Experiments were conducted and obtained results showed that the asymmetric chambers configuration has a good energy extraction over a wide range of frequencies comparatively to the symmetric chambers configuration.

With the high speed evolution of digital computers, numerical modeling has become essential when designing an OWC. Up to this date, several models have been used to describe, in a better way, the behavior of the flow and energy conversion within a numerical wave tank coupled with an OWC. First, the Boundary Element Method based on potential theory has been widely used (see João (2008) for a detailed review on the application of this method to WECs). Some authors, then, used an analogy with an oscillatory mechanical model (Karami et al., 2012; Stappenbelt and Cooper, 2010) where the free surface in the OWC chamber is modeled by a thin rigid plate that oscillates vertically due to the excitation of the incident waves. Developing all the forces acting on the plate, the motion will be described by a linear second order differential equation. The fluid forces are determined by considering a potential flow theory.

Recently, a new model called RANS-VOF has gained an enormous interest. In this model, the Reynolds-averaged Navier-Stokes (RANS) equations are coupled with the volume of fluid (VOF) technique (implemented first by Hirt and Nichols (1981)) which is used to capture the interface between two different phases. Some CFD open source and commercial software supporting this model such as OpenFOAM, ANSYS CFX, and ANSYS FLUENT were used and applied successfully by several researchers to various types of wave energy converters especially the OWC. Liu et al. (2010) analyzed the effect of the incident wave period and shape parameters on the relative amplitude in the OWC chamber by using FLUENT software. Teixeira et al. (2013) investigated the OWC geometry and the turbine char-