Ocean Engineering 102 (2015) 40–50

Contents lists available at ScienceDirect

Ocean Engineering

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

Numerical investigations of the hydrodynamics of an oscillating water column device

Arun Kamath*, Hans Bihs, Øivind A. Arntsen

Department of Civil and Transport Engineering, Norwegian University of Science and Technology, 7491 Trondheim, Norway

ARTICLE INFO

Article history:
Received 22 May 2014
Accepted 13 April 2015
Available online 16 May 2015

Keywords:
Oscillating water column
Computational fluid dynamics
Wave energy
Porous media
REEF3D

ABSTRACT

An oscillating water column (OWC) device is a renewable energy device that is used to extract ocean wave energy through the action of waves on a partially submerged chamber consisting of an air and a water column. The operation of an OWC device involves complex hydrodynamic interactions between the waves and the device and a good understanding of these interactions is essential for the design of hydrodynamically efficient and structurally stable devices.

In this paper, a two-dimensional numerical wave tank is utilized to simulate the interaction of an OWC device with waves of different wavelengths and steepnesses. The chamber pressure, provided by a turbine in a prototype, is simulated using porous media flow theory in the numerical model. The pressure in the chamber and the velocity of the free surface are calculated to evaluate the efficiency of the device and the model is validated by comparing the numerical results with experimental data. The performance of the device under a range of wavelengths for different wave steepnesses is evaluated. The effect of wave steepness on the device efficiency at a lower wave steepness was found to be low, but a large reduction in performance was found in the presence of steep non-linear waves.

1. Introduction

An oscillating water column (OWC) device is a renewable energy device that is used to capture ocean wave energy and convert it to electrical energy. An OWC device consists of a chamber that is partially submerged in water and has an air column trapped above the water column. The water column in the chamber is excited by the incoming waves and the motion of the water column is transferred to the air column which is forced through a vent at the roof of the chamber. The pressurized air flows through the vent and drives a turbine to generate electrical energy. A good understanding of the hydrodynamics around an OWC device is essential in order to efficiently harness wave energy and to develop stable and economical OWC devices.

Several researchers have mathematically analyzed the hydrodynamics of an OWC device and devised formulae to evaluate the hydrodynamic efficiency. Evans (1978) calculated the efficiency of a wave energy converter modeled as a pair of parallel vertical plates, with a float connected to a spring-dashpot on the free surface as the wave energy absorber. This model considered the length of the chamber to be small compared to the waves and the water column moves like a weightless piston, resulting in a one-dimensional rigid motion of the free surface. Evans (1982) further studied the OWC device, including the spatial variation of the free surface and related the hydrodynamics to the dynamic air pressure developed in the chamber. This is considered to be a better representation of the system, as the free surface motion does not need to be piston-like under all operating conditions. Sarmento and Falcao (1985) developed a theory to evaluate the hydrodynamic efficiency of an OWC device with both linear and non-linear power take-off (PTO) systems. The authors concluded that the non-linear PTO was only marginally lower in efficiency compared to the linear system. They also noted that the device efficiency could be improved by introducing phase control, where the volume flow of air is controlled independently of the pressure by varying the external damping on the chamber. Sarmento (1992) carried out wave flume experiments of an OWC device using a small amplitude-to-wavelength ratio, A_0/λ and validated the theory presented by Sarmento and Falcao (1985). The external damping from a power take-off device was modeled using porous filter material and orifice plates to represent linear and non-linear PTO mechanisms respectively. The importance of external damping was presented by Thiruvenkatasamy and Neelamani (1997), who studied the effect of the nozzle area on the efficiency of an OWC device through wave flume experiments. In their experiments, the air pressure in the chamber was lowered for nozzle cross-sectional areas greater than 0.81% of the free surface,

* Corresponding author. Tel.: +47 73 59 46 40; fax: +47 73 59 70 21.
E-mail address: arun.kamath@ntnu.no (A. Kamath).

http://dx.doi.org/10.1016/j.oceaneng.2015.04.043
0029-8018/

resulting in a lower device efficiency. This implies that an optimal damping on the chamber is required under prevalent wave conditions in order to efficiently extract the incident wave energy. 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. They reported a peak efficiency of about 0.7 and that the shape parameters of the device affect the bandwidth of the hydrodynamic efficiency curve. They concluded that a hydrodynamically smooth front wall slightly reduced the entrance losses, resulting in a slightly larger amount of wave energy available in the device chamber. Zhang et al. (2012) simulated the experiments presented by Morris-Thomas et al. (2007) with a two-dimensional computational fluid dynamics (CFD) based numerical model and presented the variation of the pressure and the free surface elevation inside the chamber, however without comparison to the experimental data. They reported reasonable agreement with experimental data for the hydrodynamic efficiency of the device with a slight over prediction of the efficiency in the model due to the complex pressure changes in the chamber around resonance. Teixeira et al. (2013) used a numerical model based on the semi-implicit Taylor–Galerkin method to simulate regular wave interaction with an OWC device including the aerodynamics in the chamber using the first law of thermodynamics and ideal gas transformation and compared their results with numerical results from the commercial CFD code Fluent. López et al. (2014) validated a CFD model using experimental results and studied the importance of external damping on the performance of an OWC device under regular and irregular waves to determine the optimum turbine-induced damping on an OWC device.

The OWC device absorbs wave energy through the motion of the air column that is pressurized due to the damping provided by the air vent and the power take-off device. This external damping on the device chamber is represented by a nozzle or vent in the roof of the chamber in experimental studies by Thiruvenkatasamy and Neelamani (1997) and Morris-Thomas et al. (2007). Sarmento (1992) used orifice plates and porous filter material. The use of a porous filter material in model testing is one of the methods to represent a linear power take-off device. This is justified by the fact that a Wells turbine is approximately linear and this simple method provides a good representation of the linear pressure-versus-flow rate characteristics (Falcao and Henriques, 2014). In a numerical model, the effect of a power take-off device can be simulated by considering the air flow in the vent as a flow through a porous medium. In the case of a linear power take-off device, the pressure drop across the vent due the presence of the porous medium can be governed by a linear pressure drop law. It is also possible to numerically implement a quadratic pressure drop law to simulate the effect of a self-rectifying impulse turbine. This method provides a good representation of the external damping on the device chamber to study the device hydrodynamics without difficulties in numerical computations due to the high air velocities in an air vent of a small width.

In current literature, there are not many numerical studies which control external damping in an explicit manner without changing the size of the air vent. Didier et al. (2011) used the porous media theory to define external damping on an OWC device modeled as a cylinder of small diameter. The application of the porous media flow theory to model the pressure drop across the vent on model scale OWC devices would help in understanding the hydrodynamics of the device in combination with the effect from the PTO device. The use of porous media flow theory to model the external damping provides the means to control the variation of the chamber pressure. The control over the chamber pressure variation is part of a strategy to improve the performance of the device, called phase control. This concept has been presented by several authors, for example Hoskin et al. (1986), Falcao and Justino (1999) and Lopes et al. (2009). A combined approach to model the variation of the free surface and the chamber pressure and control the pressure drop across the vent in the numerical model will provide useful insights into the operation of the device.

The objective of this study is to investigate the hydrodynamics of an OWC device including the variation of the free surface and pressure inside the chamber and represent the external damping provided by the PTO device using the porous media flow theory. The study uses a CFD model to carry out two-dimensional simulations of an OWC device placed in a numerical wave tank. The experimental data from Morris-Thomas et al. (2007) is used to validate the numerical model. The pressure drop in the experiments is quantified using the porous media flow theory and the external damping on the chamber is defined independent of the air vent width in the numerical model. The numerical model assumes incompressible air in the device chamber because the effect of air compressibility is negligible in the small scale model considered in this study as the ratio between the chamber volume and the OWC free surface is relatively small and much smaller than in a full-scale prototype. The variation of the free surface, chamber pressure and the velocity of the vertical free surface motion in the numerical model are compared to the experimental observations. The efficiency of the device over a range of wavelengths is calculated for a fixed wave amplitude. In real sea states, the incident wave amplitude may change over time. In order to investigate the performance of the device under changing conditions in the sea states, the effect of wave steepness on the device efficiency and performance under steep non-linear waves is evaluated. The knowledge gained from these studies using regular waves can help in obtaining a better understanding of the device performance under different wave steepnesses and amplitudes that are encountered in real sea states.

2. Numerical model

The open-source CFD model REEF3D solves the fluid flow problem using the incompressible Reynolds-averaged Navier–Stokes (RANS) equations along with the continuity equation:

$$\frac{\partial U_i}{\partial x_i}=0 \tag{1}$$

$$\frac{\partial U_i}{\partial t}+U_j\frac{\partial U_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left[(\nu+\nu_t)\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\right]+g_i \tag{2}$$

where U is the velocity averaged over time t, ρ is the fluid density, P is the pressure, ν is the kinematic viscosity, ν_t is the eddy viscosity and g is the acceleration due to gravity.

Chorin's projection method (Chorin, 1968) is used to determine the pressure and a preconditioned BiCGStab solver (van der Vorst, 1992) is used to solve the resulting Poisson pressure equation. Turbulence modeling is handled using the two-equation k–ω model proposed by Wilcox (1994), where the transport equations for the turbulent kinetic energy, k, and the specific turbulent dissipation rate, ω, are

$$\frac{\partial k}{\partial t}+U_j\frac{\partial k}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\nu+\frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+P_k-\beta_k k\omega \tag{3}$$

$$\frac{\partial \omega}{\partial t}+U_j\frac{\partial \omega}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\nu+\frac{\nu_t}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right]+\frac{\omega}{k}\alpha P_k-\beta\omega^2 \tag{4}$$

$$\nu_t=\frac{k}{\omega} \tag{5}$$