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Experimental and theoretical study of a cylindrical oscillating water column device with a quadratic power take-off model

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ABSTRACT

The wave power extraction by a cylindrical oscillating water column (OWC) device with a quadratic power take-off (PTO) model was studied experimentally and theoretically. In the experiment, a scaled model OWC was tested in a wave flume, with an orifice being used to simulate a quadratic PTO mechanism. In the theoretical analysis, the quadratic PTO model was linearized based on Lorenz's principle of equivalent work, which allows us to perform a frequency domain analysis using an eigen-function matching method. The effects of higher harmonic components and the spatial non-uniformity of the surface velocity inside the chamber were discussed. A semi-analytical model was proposed to understand the viscous loss affecting the measured capture length. Our treatment of the quadratic PTO model was validated by comparing quasi-linear theoretical capture length and the laboratory measurement. Our results also showed that the effects of spatial non-uniformity and viscous loss could be noticeable for shorter waves.

1. Introduction

With the surging demand of global energy consumption and the progressive depletion of fossil fuel resources, the need for renewable, clean and affordable new energy sources has emerged and developed quickly over the past a few decades. Ocean wave energy, being a form of solar energy, has been proved to be a huge and yet under-utilized renewable energy source [1]. Ocean wave energy is more evenly distributed due to the long-distance energy transmission by swells. Hence ocean wave energy can be more persistent and less spatial-dependent compared to wind energy. It has been estimated that the total ocean wave energy potential globally is on the order of terawatt (10^{12} W)[2].

The oil crisis of the 1970s inspired the research and development of renewable energy across the world, together with it was an increase in the research related to the wave energy utilization using wave energy converters (WECs). WEC devices can be categorized by their operation locations, types and operation modes [1,3]. Oscillating water column (OWC) type of wave energy converters is one of the most widely researched and applied WEC devices. This type of WEC device generally utilizes a constrained air chamber above the water surface with a turbine mounted to the top of the chamber for electricity generation; the bottom of the chamber is submerged and open so that the incident wave creates a pressure fluctuation at the lower submerged opening, causing a water column oscillation inside the OWC chamber. The oscillation of the water surface compresses the air inside the chamber, and forces the air to flow through the turbine to generate electricity.

While the first wave conversion device was implemented to drive navigation buoys as early as in the 1940s, it was the experimental work by Salter [4] that inspired the widespread government interests in the development of WECs. Evans [5] first developed a complete theory based on linear wave theory to characterize the energy conversion of a rigid-body oscillating device. Because the model was intended for rigid body oscillation, early theoretical studies of OWC devices assumed an incompressible air and treated the water surface inside the chamber as a weightless rigid piston [6]. Theoretically, this assumption of weightless rigid piston is valid only if the chamber size is small compared to the incident wave length; if the dimension of the OWC device is not small, effects of spatial non-uniformity of the water surface inside the chamber can be important. Evans [7] also developed a reciprocal relationship to account for the non-uniformity of the water surface inside the chamber due to wave diffraction. Sarmento and Falcão [8]

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considered air compressibility in their theoretical work. Evans and Porter [9] studied a simple truncated cylindrical tube-type OWC device using a matched eigenfunction expansion method. Recent theoretical studies such as those by Martin-Rivas and Mei [10], Lovas et al. [11] and Deng et al. [12,13] also used matched eigenfunction expansion methods to study various cylindrical OWC devices deployed near-shore or at the shoreline.

Prototype or scaled experiments are the best way to investigate the performance and the physics underlying this complex water-structure-air interaction process. Prototype experiments of OWC devices have been carried out in some places over the past few decades, including the Portugal 400 kW OWC plant at the Island of Pico, Azores [14] and the Land Installed Marine Powered Energy Converter (LIMPET) constructed in Scotland. Goda et al. [15] reported the construction of an OWC device incorporated with a caisson breakwater, and Washio et al. [16] reported a prototype floating OWC device, the Mighty Whale, installed in Japan.

Scaled experiments conducted in controlled environments (in a laboratory or a sheltered coast) have also been carried out by many researchers in the past, mainly for validation of theories. Falcão and Henriques [17] discussed about the model-prototype similarity issues encountered in OWC laboratory experiments. Challenges facing scaled experiments in laboratory include consideration of air compressibility, correct representation of the air turbine used for electricity generation, and the measurement of the complex water surface inside the OWC chamber. To consider the non-uniformity of the water surface inside their rectangular OWC chambers, Morris-Thomas et al. [18] and He et al. [19] have tried to measure the surface elevations at two or more locations inside their OWC chambers. However, for cylindrical OWC devices where wave scattering is complicated, it is difficult to obtain a good description of the water surface non-uniformity using traditional devices such as wave gauges. Therefore, only one wave gauge is usually deployed inside the OWC chamber (e.g., [20]), which in the case of relatively short waves, can cause a misrepresentation of the water surface motion inside the OWC chamber and affect the accuracy in the measured energy extraction efficiency.

In previous theoretical studies of OWC devices, major assumptions have been made on the power take-off (PTO) model and the viscous loss of wave energy. In order to obtain analytical solutions using linear wave theory, a linear PTO model was normally assumed and viscous effects were not considered in the published theoretical studies of OWC devices. Brendmo et al. [21] proposed a way to account for the effects of the viscous loss associated with the interaction of an OWC device with water waves; however, the numerical results and their validation are not articulated in the paper. A most commonly used linear PTO mechanism in theoretical studies is a Wells Turbine, even though there are other types turbines available for engineering applications of OWC devices, such as self-rectifying impulse turbines, which are nonlinear [22,23]. For scaled laboratory studies of OWC devices, a scaled turbine model could be expensive to fabricate or otherwise unfeasible, an orifice is often used to simulate a quadratic PTO mechanism (for example, He et al. [19] and Morris-Thomas et al. [18]).

This study addresses three issues: how to implement a nonlinear PTO model in an analytical study of OWC devices, how to improve the accuracy in wave extraction efficiency measured in wave flume tests on circular OWC devices, and how to estimate the viscous loss. The methodology is demonstrated by studying a bottom-resting OWC device comprised of a cylindrical tube sector with a co-axial C-shaped supporting structure, which has been studied analytically by Deng et al. [12] using a linear PTO model. Experimental results are presented to validate the treatment of a quadratic PTO model. The experimental results are compared to the theoretical calculations based on this quadratic PTO model, and the quantification of viscous loss is estimated by a semi-analytical model. We will also discuss the error introduced by one-point water surface measurement inside the chamber.

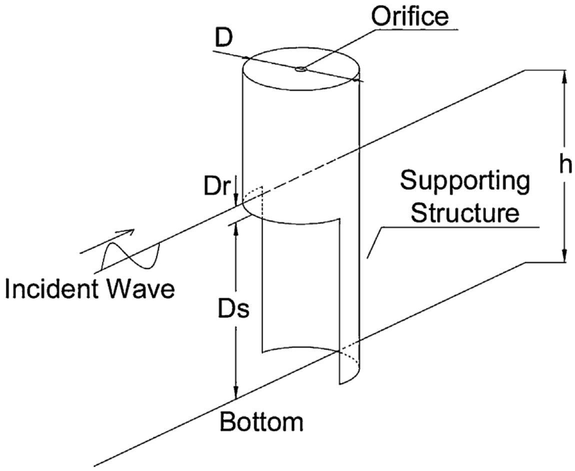

Fig. 1. A sketch of the OWC device.

2. Experimental setup, test conditions and data analysis

The experiment was performed in a wave flume located in the Hydraulic Modeling Laboratory of Nanyang Technological University, Singapore. The flume had dimensions of 32.5 m in length, 0.55 m in width and 0.6 m in depth. The sidewall and bottom of the flume were made of glass. At one end of the flume, a piston-type wave maker was installed and at the other end, an absorption slope of 1:15 covered by porous material was used to absorb wave energy and reduce wave reflection from the absorption slope. The wave reflection from the absorption slope was small enough to be neglected: the measured reflection coefficient was less than 0.05 according to He and Huang [24].

2.1. The OWC model

Referring to Fig. 1, the OWC model used in this experiment is a covered tube sector with one orifice in the center of the top cover. The tube sector is supported by a C-shaped structure with the opening angle being 180°. The distance from the lower tip of the OWC chamber to the flume bed is 25 cm (the distance D_s in Fig. 1). The model has an overall dimension of 40 cm in total height. The draft of the OWC chamber, $D_r = h - D_s$, can be changed by changing the water depth h.

Fig. 2 shows the OWC model installed in the wave flume. The OWC model was made of stainless steel, with the inner diameter of the cylinder D being 12.5 cm and the thickness of the stainless steel plate being 3 mm. On the top of the tube sector an orifice of diameter 1.4 cm was used to simulate a nonlinear turbine. In this study, the lower tip of the OWC chamber was rounded to reduce the power loss due to vortex shedding at the edge (see Appendix C).

Referring to Fig. 3, the OWC model was placed at 18.5 m from the wave generator (measured from the back side of the OWC model). The model was secured firmly in the flume by using four steel bars attached to the two sidewalls of the flume. Two UltraLab ultrasonic sensors, S1 and S2, were placed 11 m and 6 m from the model center-line, respectively; these two sensors were used to measure the incident wave. Three resistance wave gauges were used to monitor the waves inside and near the OWC model: G1 was placed at 5 cm from the frontal edge of the cylinder, G2 inside the cylinder, and G3 at 5cm from the back edge of the cylinder. G2 measured the water surface elevation time series inside the OWC chamber so