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Numerical and experimental investigation of wave dynamics on a land-fixed OWC device

De-Zhi Ning [a,*], Rong-Quan Wang [a], Ying Gou [a], Ming Zhao [b], Bin Teng [a]

[a] State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, 116024, China
[b] School of Computing, Engineering and Mathematics, Western Sydney University, Locked Bag 1797, Penrith, NSW, 2751, Australia

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ABSTRACT

An Oscillating Water Column (OWC) Wave Energy Converter (WEC) is a device that converts the energy of ocean waves to electrical energy. When an OWC is designed, both its energy efficiency and the wave loads on it should be considered. Most attentions have been paid to the energy efficiency of an OWC device in the past several decades. In the present study, the fully nonlinear numerical wave model developed by Ning et al. (2015) [1] is extended to simulate the dynamic wave forces on the land-fixed OWC device by using the acceleration potential method, and the experimental tests are also carried out. The comparisons between numerical results and experimental data are performed. Then the effects of wave conditions and chamber geometry on the wave force on the front wall of the chamber are investigated. The results indicate that the total wave force decreases with the increase of the wavelength and increases with the increase of the incident wave height. The wave force is also strongly influenced by the opening ratio, i.e., in the low-frequency region, the larger the opening ratio, the smaller the wave force and it shows an opposite tendency in the high-frequency region.

1. Introduction

Due to its non-polluting nature and environment friendliness, renewable energy has attracted increasing attention and renewable energy harvesting technique has been the topics of many theoretical and empirical studies [2]. Wave energy is considered to be one of the most promising forms of clean renewable energy because of its high energy flux density and low negative environmental impact. To harvest the wave energy, various types of Wave Energy Converters (WECs) have been proposed. Due to their high efficiency and structural simplicity, OWC devices are believed to be feasible devices to harvest wave energy and the performance of OWC devices has been studied extensively in the past decades [3]. An OWC device generates energy from the cyclic rising and falling of water in an air chamber caused by waves in the ocean as shown in Fig. 1. The incoming waves make the water surface inside the air chamber oscillate. The air is driven in and out of the chamber through a power-take-off system, which is represented by a small hole on the roof of the chamber as shown in Fig. 1.

The chamber design and the turbine characteristics are important factors that affect the efficiency of an OWC device. To achieve the optimum hydrodynamic efficiency, numerous studies have been carried out either experimentally [2,4–6] or numerically [1,7–9] to optimize the chamber design of OWC devices. Because the turbine plays a very important role in the energy conversion, the effect of turbine characteristics on the efficiency are studied by many researchers [8,10–13]. Studies have also been carried out to investigate the effects of wave conditions [14–17] and sea bottom profiles [18–21] on the hydrodynamic efficiency of OWC devices.

However, most of the previous studies about OWC devices were focused on the overall hydrodynamic efficiency, the dynamic wave loads on the OWC devices have been paid little attention. The large difference between the internal and external water surface levels of the chamber can cause a dynamic wave load on the front wall of the chamber, which may be a threat to the safety operation of OWC devices [22]. The largest bottom standing wave energy plant (OSPREY plant in Scotland) was destroyed by the sea shortly after installment [7] and the concrete subsurface structure of the Pico plant in Portugal was significantly damaged by waves [22]. As the working in the ocean is both dangerous and expensive, it could be more cost effective to sacrifice some overall wave energy conversion efficiency to ensure the safety of the system [23]. An experimental study was carried out by Ashlin et al. [24] to investigate the

* Corresponding author.
E-mail address: dzning@dlut.edu.cn (D.-Z. Ning).

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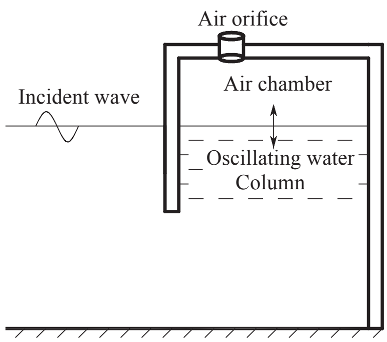

Fig. 1. Sketch of an OWC device.

horizontal and vertical wave forces on the OWC devices. Their study was mainly focused on the effects of the wave steepness and the relative water depth on the wave loads. To provide better understanding of the wave forces acting on the OWC device and provide a guidance for the device design and safe operation, it is important to find out the factors that affect the wave dynamics through a systematic study. In the present study, the effects of wave conditions and chamber geometry on the wave loads on the front wall are studied both numerically and experimentally over a wide range of wave conditions and OWC chamber dimensions.

The rest of the present paper is organized as follows. The numerical model is introduced and the experimental procedure is described in Section 2 and Section 3, respectively. Then, the comparison between numerical results and experimental data, the effects of wave conditions and chamber geometry on the wave loads on the front wall are discussed in detail in Section 4. Finally, the conclusions of this study are summarized in Section 5.

2. Numerical model

To investigate the hydrodynamic performance of a land-fixed OWC, the two-dimensional (2-D) fully nonlinear numerical wave flume based on the potential theory and time-domain HOBEM developed by Ning et al. [1] was used to simulate the wave interaction with the fixed OWC device. The numerical model is extended to simulate the nonlinear wave forces on the structure in the present study. The sketch of the numerical wave flume is shown in Fig. 2. A Cartesian coordinate system Oxz is chosen with its origin on the still water level, and the z-axis pointing upward. In Fig. 2, h denotes the static water depth, B the chamber width, C the thickness of the front wall, d the immersed depth of the front wall, L_d the length of the damping zone, L_o the width of the orifice and h_c the height of the air chamber above the still water level. The potential flow theory assumes that the fluid is incompressible, inviscid, and the fluid motion is irrotational. The fluid motion can therefore be described by the velocity potential ϕ related to the fluid velocity. In the time-domain HOBEM model by Ning et al. [1], the incident waves are generated using the inner sources in the computational domain, the governing equation is described with Poisson equation and a damping layer with a damping coefficient $\mu_1(x)$ at the inlet of the numerical flume is applied to absorb the reflected waves from the OWC device. To model the viscous effect due to the water viscosity and the flow separation in the potential flow model, linear damping terms can be introduced into free surface boundary conditions. This technique has been used to study water sloshing in a container [25] and wave surface elevation in the narrow gap between twin floating objects [26,27]. In this study, an artificial viscous damping term with a damping coefficient μ_2 is applied to the dynamic free surface boundary condition inside the OWC chamber in the numerical model. Thus, the fully nonlinear free surface boundary conditions are modified as

$$\begin{cases} \dfrac{\mathrm{d}\vec{X}(x,z)}{\mathrm{d}t} = \nabla\phi - \mu_1(x)\left(\vec{X} - \vec{X}_0\right) \\ \dfrac{\mathrm{d}\phi}{\mathrm{d}t} = -g\eta + \dfrac{1}{2}|\nabla\phi|^2 - \dfrac{p_a}{\rho} - \mu_1(x)\phi - \mu_2\dfrac{\partial\phi}{\partial n} \end{cases}, \tag{1}$$

where $\vec{X}(x,z)$ denotes the position vector of a fluid particle on the free surface and $\vec{X}_0(x_0,0)$ the initial static position of the fluid particle, η the vertical elevation of the free surface, g the gravity acceleration, ρ the water density and t the time. The material derivative is defined as $\mathrm{d}/\mathrm{d}t = \partial/\partial t + \nabla\phi\cdot\nabla$. The damping coefficient $\mu_1(x)$ is defined by

$$\mu_1(x) = \begin{cases} \omega\left(\dfrac{x - x_1}{L_d}\right)^2, & x_1 - L_d < x < x_1 \\ 0, & x \geq x_1 \end{cases}, \tag{2}$$

where x_1 is the starting position of damping zone, L_d is the length of the damping zone given to be 1.5 times the incident wavelength (i.e., 1.5L, where L is the wavelength) in the present study. The artificial viscous damping coefficient μ_2 is determined by trial and error method by comparison with the experimental data and is only implemented inside the chamber.

Outside of the chamber, the air pressure p_a on the free surface is set to be zero (i.e., atmospheric pressure), while inside the chamber, the pneumatic pressure is specified on the free-surface:

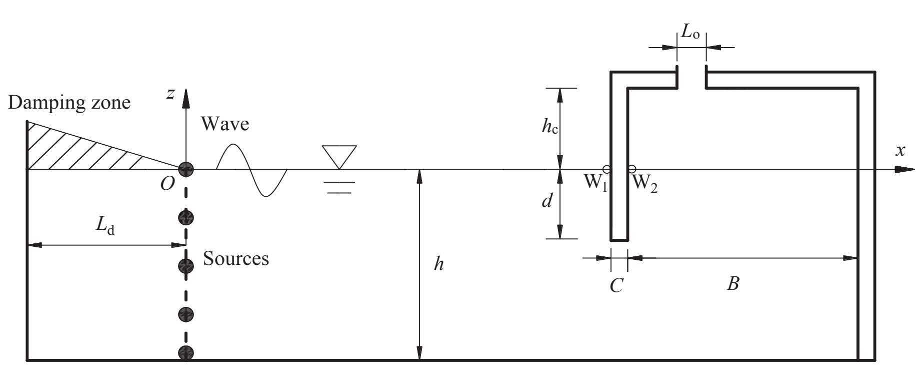

Fig. 2. Sketch of the numerical wave flume.