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Nonlinear and viscous effects on the hydrodynamic performance of a fixed OWC wave energy converter

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ABSTRACT

The hydrodynamic performance of a fixed Oscillating Water Column (OWC) device is experimentally and numerically investigated. Based on the time-domain higher-order boundary element method (HOBEM), by introducing an artificial viscosity term in the dynamic free surface boundary condition, a fully nonlinear numerical wave model is used to simulate the hydrodynamic performance of an OWC device. A set of comprehensive experiments for regular waves is carried out to validate the numerical results as well as to investigate the nonlinear effects on the hydrodynamic performance of OWC. The mechanism of the nonlinear phenomenon is investigated based on the analysis of the experimental and numerical results. The influence of the wave nonlinearity and the viscosity on the hydrodynamic efficiency is quantified by comparing the linear and nonlinear numerical results. It was found that the hydrodynamic efficiency increases with the nonlinearity and viscosity when the incident wave amplitude is small. When the incident wave amplitude is large, the hydrodynamic efficiency is reduced by the weakened transmission of the second-order harmonic wave component due to the strong wave nonlinearity. However, when the wave amplitude is between these two regimes, the wave is weakly nonlinear, the efficiency decreases with the wave amplitude due to the combined effect of the nonlinearity and viscosity.

1. Introduction

Given its high power density, wave energy has the potential to become the lowest cost renewable energy source. In addition, it has the advantage of uninterrupted and continuous supply of energy over other renewable energy, such as wind and tidal energy. A wide variety of technologies are developed to harvest wave energy. OWC devices are believed to be one of the most popular wave energy converters (WECs) for viable wave energy harvesting. Yet the hydrodynamic performance of the OWC device remains not well-understood due to various factors, such as chamber geometry, wave nonlinear, water viscosity and power take-off damping. The influences of the nonlinearity and viscosity on the hydrodynamic performance are especially complex. The wave nonlinearity and viscosity are neglected in the theoretical study of the hydrodynamic performance of OWC devices (Evans, 1978, 1982; Falnes and McIver, 1985; McCormick, 1976) based on linear potential wave theory. Therefore, the hydrodynamic efficiency is often over-predicted.

Various nonlinear wave models have been developed to investigate the hydrodynamics of OWC (Elhanafi et al., 2016; Koo and Kim, 2010; Luo et al., 2014; Ning et al., 2015). It is found that hydrodynamic efficiency of the device is highly influenced by the incident wave amplitude for the given OWC geometrical parameters (Elhanafi et al., 2016; Luo et al., 2014; Ning et al., 2015, 2016). However, the influence of wave nonlinearity on OWC hydrodynamic efficiency is complex. The numerical simulations by Luo et al. (2014) suggest that the efficiency decreases with the wave amplitude. In contrast, the numerical and experimental studies by Ning et al. (2015, 2016) indicate that the hydrodynamic efficiency increases with wave amplitude first to a maximum value and deceases with wave amplitude thereafter. Through numerical study, Elhanafi et al. (2016) demonstrates that the hydrodynamic efficiency increases with the wave amplitude only when the damping factor is very small. However, there is a lack of understanding of the mechanism behind these phenomena. Luo et al. (2014) applied Fast Fourier Transform (FFT) to analyze the incident wave surface elevation and the transient air velocity at the outlet of the OWC. They attributed the decreased efficiency with wave amplitude to the energy transfers from the primary

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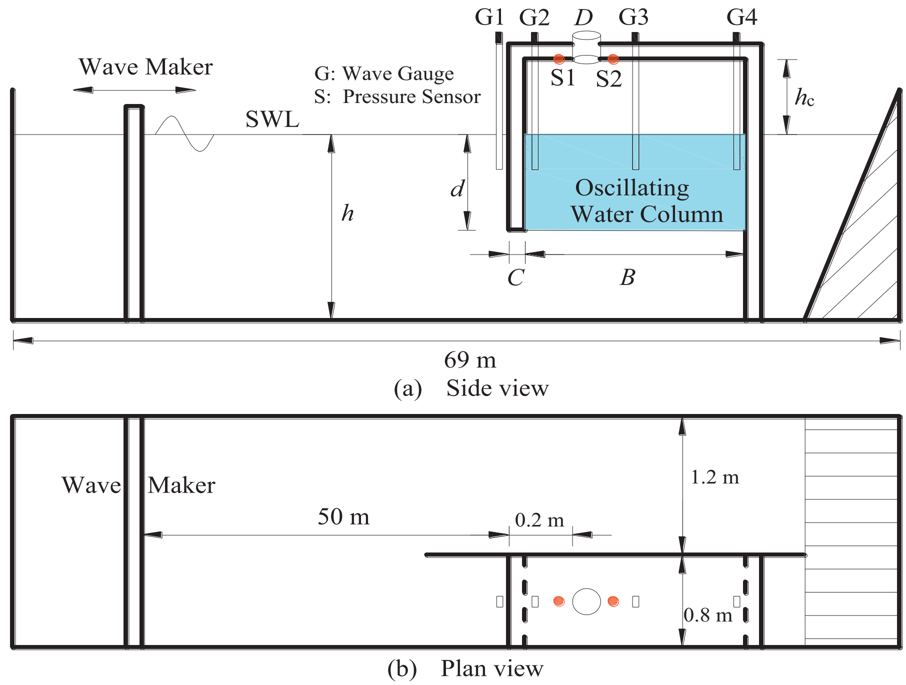

Fig. 1. Schematic of the experimental setup.

wave to the second-order wave component. However, the efficiency is more directly related to the inner surface motion than the incident wave surface. Therefore, it is worth to carry out a more systemic and comprehensive study of the influence of wave nonlinearity on the OWC efficiency.

Nonlinear wave interaction leads to energy transfer among different wave components at difference frequency. The wave dissipation is frequency dependent (Zou, 2004). Furthermore, the wave nonlinearity can produce local surface vortices (Filatov et al., 2016) which, of course, would also generated further energy dissipation. Accurately predicting the dissipation of gravity waves is a challenging problem due to wave nonlinearity, complex free surface deformation and evolution for steep and breaking wave (Bouscasse et al., 2014; Colagrossi et al., 2013, 2015; Iafrati et al., 2013; Lubin and Glockner, 2015; Wang et al., 2009). Energy loss occurs both at the entrance when incident waves enter the chamber and inside the chamber after wave generate an up-and-down motion of free surface within the chamber (He et al., 2016; Koo and Kim, 2010; Kuo et al., 2017; Müller and Whittaker, 1995; Tseng et al., 2000). Previous results of flow field suggest that the energy loss is affected by the wave conditions and the geometry of the front wall (Elhanafi et al., 2016; Fleming and Macfarlane, 2017; Kamath et al., 2015; López et al., 2015a; Teixeira et al., 2013; Vyzikas et al., 2017). Most of the OWC study that account for the energy loss due to the water viscosity were carried out using the Reynolds Averaged Navier-Stokes (RANS) equations (Elhanafi et al., 2016; Iturrioz et al., 2015; Kamath et al., 2015; López et al., 2014, 2016; Liu et al., 2016; Luo et al., 2014; Pereiras et al., 2015; Teixeira et al., 2013; Zhang et al., 2012). Babarit et al. (2012) and Iturrioz et al. (2014) introduce a friction force to take into account the viscous and turbulent losses at the chamber entrance by using Boundary Element Method (BEM). Additionally, the viscous effect may be incorporated by adding an artificial viscous damping term to the dynamic free surface boundary condition of the potential flow wave model (Koo and Kim, 2010; Ning et al., 2015). Although both these types of model have been shown to be in good agreement with the experimental data in the presence of viscosity (Wolgamot and Fitzgerald, 2015), it is not clear to what extent the viscosity would affect the hydrodynamic performance of OWC.

The main objective of this study is to elucidate the mechanism behind the nonlinear behavior in the OWC hydrodynamic performance. The influences of the wave nonlinearity and the viscosity on the hydrodynamic performance are investigated by comparing the linear and nonlinear numerical results. And the influence of the nonlinearity and the viscosity on the hydrodynamic efficiency is quantitative analyzed for the first time.

The rest of the present paper is organized as follows: The experimental procedure and numerical model are described in Section 2. In Section 3, the comparisons between the numerical results and experimental data are carried out firstly. Then, the nonlinear and viscous effects on the hydrodynamic performance of the OWC device are given in detail. Finally, the conclusions of this study are summarized in Section 4.

2. Model

2.1. Experimental model

The physical model tests were carried out in the wave-current flume at the State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, China. The wave-current flume is 69 m long, 2 m wide and 1.8 m high. It is equipped with a piston-type unidirectional wave maker that can generate regular and irregular waves with periods from 0.5 s to 5.0 s. The test section of the wave flume was divided into two parts along the longitudinal direction, which were 1.2 m and 0.8 m wide, respectively. The OWC model was installed at the part of 0.8 m wide and 50 m away from the wave maker (see Fig. 1). The OWC model was designed to span across the entire width and depth of the flume (i.e., the width of the flume $w = 0.8$ m). Fig. 1 shows the schematic of the experimental setup. The water depth h is 0.8 m, front wall thickness C is 0.04 m, chamber height h_c is 0.2 m, chamber width B is 0.55 m and front wall draft d is 0.14 m. The orifice was located on the ceiling of the chamber and was 0.2 m from the front wall. Note that it was not placed at the chamber center, due to the fact that there was a wave gauge fixed at the center of the ceiling. According to previous experimental studies (He and Huang, 2014; Ning et al., 2016), the optimal efficiency occurs at the opening ratio of $\alpha = S_0/S = 0.66\%$ (where S_0 and S are the cross-sectional areas of the orifice and the air-chamber ceiling, respectively). Thus, in the present study, the orifice diameter $D = 0.06$ m is chosen with the opening ratio $\alpha = 0.66\%$. Four wave gauges (i.e., G1 - G4) were used to