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A tunable resonant oscillating water column wave energy converter

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ABSTRACT

A novel wave energy converter (UREWEC), which is constructed by attaching a U-tube to a traditional oscillating water column WEC, is proposed. To improve the performance of the UREWEC at lower wave frequencies, the two sides of the U-tube are sloped. A mathematical model based on potential theory is used to examine the wave energy extraction efficiency of the UREWEC. The analytical results show that the wave energy extraction efficiency of the UREWEC can reach 100% at the optimal frequency if the viscosity and nonlinearity are ignored. The optimal frequency of the UREWEC can be instantaneously adjusted by controlling the amount of the fluid in the U-tube and the turbine rotational speed. The sloped sides of the U-tube are beneficial to obtain a lower UREWEC optimal frequency. A smaller cross-sectional area of the U-tube can extend the adjusted ranges of the optimal frequency while increasing the wall-friction losses.

1. Introduction

Large amount of energy is predicted to be required in future, which may lead to very serious environmental problems. Developing pollution-free energy resources becomes an urgent task for humans. Wave energy is one of the promising candidates. Among the many existed types of wave energy converters (WECs), the oscillating water column WEC (OWCWEC) is considered as the most possible candidate that can be commercialized.

Improving the electrical power output is the key to maintain the competitive advantage of OWCWECs. Two methods are available to obtain higher electrical power output from an OWC device: (i) increasing the energy absorbed from the waves; (ii) decreasing the losses in the energy-conversion chain.

The hydrodynamic behavior of WECs is very important to improve their wave energy extraction efficiency. Until now, many theoretical studies have been carried out on the hydrodynamic performance of OWCs. In earlier studies (Evans, 1978), the OWC hydrodynamics was modeled by assuming that the interior free surface (free surface in the OWC chamber) moves similar to a weightless piston. Later, some scholars (Evans, 1982; Sarmento and Falcao, 1985) modeled the OWC hydrodynamics by applying an oscillating pressure on the interior free surface and considered the spatial variation in the interior free surface. However, the draught in the immersed part of the OWC was assumed to be negligible in these studies. To obtain more accurate predictions, Evans and Porter (1995) employed the matched eigenfunction expansion and Galerkin method to analyze the hydrodynamic behavior of the OWC, which consisted of a thin vertical surface-piercing barrier next to a vertical wall in finite-depth water. Using a method similar to that of Evans and Porter (1995), Deng et al. (2013, 2014) developed an analytical theory to study the wave energy extraction efficiency of three-dimensional OWCWECs, Rezanejad et al. (2015) studied the dual-chamber OWCs on a stepped bottom.

To study OWC devices with complex geometries and the effects of wave nonlinearity, many numerical methods based on the potential flow theory were developed (Delaure and Lewis, 2003; Josset and Clement, 2007; Ning et al, 2015). With the improvement in computational resources, computational fluid dynamics methods, which consider the viscous effect, were employed to study the hydrodynamic and aerodynamic performance of OWC devices (Zhang et al., 2012; Luo et al., 2014; López et al., 2014). In addition to the analytical and numerical studies, the OWC performance and efficiency characteristics have also been studied using experiments (Boccotti, 2003, 2007; Gouaud et al., 2010; He et al., 2013; He and Huang, 2014) and system identification methods (Gkikas and Athanassoulis, 2014).

Both theories and experiments show that an OWC can only achieve its maximum wave energy extraction efficiency under a resonance condition. For the conventional OWC, the resonance condition cannot always be satisfied because wave conditions vary. Therefore, the wave energy extraction efficiency of the OWC becomes lower in real sea states. To force the WEC to work under the resonance condition, forced resonance control techniques have been introduced. Phase (or latching) control is one of the forced

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resonance control techniques commonly used. Most studies on latching control focus on oscillating floating-body WECs. In these studies, the motion of a floating body is locked during certain time intervals of the oscillation cycle to achieve resonance conditions, in which the velocity of a floating body is in phase with the excitation force from the incident wave. Lopes et al. (2009) studied latching control algorithms for an OWC. They provided latching of the inner free-surface movement by controlling a shut-off valve. Generally, latching control requires the prediction of the wave behavior, which may affect the stability of the control. To circumvent this problem, some causal forced resonance control algorithms, in which no anticipatory technique is required, were developed (Scruggs et al., 2013 ; Nielsen et al., 2013).

Numerical and model experimental studies validated that the forced resonance control algorithms can improve the energy absorption of the WEC from the irregular waves. However, the high cost and complexity of forced resonance control system make performance in full-scale wave power plants very difficult.

Boccotti (2003) presented a resonant wave energy converter (REWEC), which can obtain impressive natural resonance in random wind-generated waves by adjusting the pressure of the air pocket. A small-scale field experiment was carried out and the higher wave energy extraction efficiency of the new device was verified. Filianoti and Camporeale (2008) numerically studied the performance of REWEC in random waves and their results confirmed that the REWEC system can absorb more incident wave energy. The technique that tunes the eigenperiod of oscillations is very important for REWEC. For the device presented by Boccotti (2003), the variation range of the air-pocket pressure is confined. Therefore the eigenperiod range that can be adjusted is limited.

A new REWEC (hereinafter referred to as UREWEC), which is constructed by attaching a U-tube to a traditional OWCWEC, is proposed in the current paper. In the UREWEC, the eigenperiod is adjusted by the amount of the fluid in the U-tube instead of air-pocket pressure. Thus, larger variation in the eigenperiod ranges can be achieved. The mathematical model of the UREWEC is derived. The parameters that affect the wave energy extraction efficiency are discussed. The methods that make the UREWEC realize optimal energy extraction efficiency at wider ranges of incident-wave period are proposed.

2. Mathematical model of the UREWEC

Fig. 1 shows the schematic diagram of the UREWEC. The left-side part of the turbine-generator unit is a classical OWC, and the right-side part is a U-tube. Two coordinate systems, namely, x–o–z and x'–o'–z' are adopted. In the x–o–z coordinate system, horizontal coordinate x points to the opposite direction of the wave propagation with its origin located at the right-side wall of the OWC chamber, and vertical coordinate z points upward with its origin located at the still water level. In the x'–o'–z coordinate system, the origin of horizontal coordinate x' is located at the symmetrical plane of the U-tube, and vertical coordinate z'' points upward with its origin located at the still level of the fluid in the U-tube. To adjust the eigenperiod value in wider ranges, the two sides of the U-tube are sloped. The angle formed by the side of the U-tube with the horizontal is denoted as θ (see Fig. 1).

In this paper, the non-dimensional form of the mathematical model is presented. The length of chamber B_C, the water density ρ_w, and gravity acceleration g are used as characteristic quantities to normalize the other physical quantities. The velocity potential, pressure, length, area, time, angular frequency and volume flux are normalized by $\rho_w g B_c, \rho_w g B_c, B_c^{3/2} g^{1/2}, B_c^2, B_c^{1/2} g^{-1/2}, g^{1/2} B_c^{-1/2}$ and $g^{5/2} B_c^{1/2}$ respectively. We note that all quantities are dimensionless in the following expressions without special explanation.

Under the assumptions of potential flow and incompressible fluid, the wave motion can be expressed in terms of velocity potential Φ, which satisfies

$$\nabla^2 \Phi = 0 \tag{1}$$

On solid boundaries (including the wall of the OWC chamber and water bottom), the water particle velocity in the normal direction must be zero.

$$\frac{\partial \Phi}{\partial n} = 0 \tag{2}$$

At the free-surface, the linearized boundary conditions are expressed as

$$\frac{\partial^2 \Phi}{\partial t^2} + \frac{\partial \Phi}{\partial z} = \begin{cases} 0, & \text{at} \quad z = 0,\ x > 1 \\ -\frac{\partial P(t)}{\partial t}, & \text{at} \quad z = 0,\ 0 < x < 1 \end{cases} \tag{3}$$

where $P(t)$ is the fluctuating air pressure in the OWC chamber.

To solve the governing Eq. (1) with boundary conditions (2) and (3), the expression for $P(t)$ must be given. The fluid motion in the U-tube and the turbine characteristics are analyzed to obtain $P(t)$. Referring to Fig. 1, the Bernoulli equation for the unsteady potential flow in the U-tube is expressed as

$$\frac{\partial \Phi_1}{\partial t} + z_1' + p_1 = \frac{\partial \Phi_2}{\partial t} + z_2' \tag{4}$$

where Φ_1, z_1', and p_1 are the velocity potential, vertical coordinate, and pressure at point 1 respectively, and Φ_2 and z_2' are the velocity potential and vertical coordinate at point 2 respectively. In this study, gauge pressure is adopted. Therefore, the pressure at point 2 is equal to zero.

The pressure difference between p_1 and $P(t)$ is a function of turbine volume flux Q. The representation of the function depends

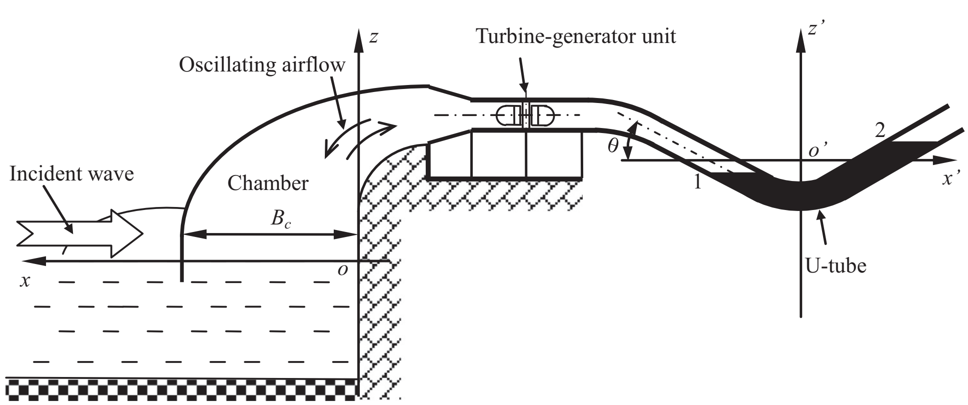

Fig. 1. Schematic diagram of the UREWEC.