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Effect of inclination on oscillation characteristics of an oscillating water column wave energy converter

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ABSTRACT

Oscillating water column (OWC) wave energy converters are adopted in many marine applications such as buoys. This research investigates how inclination-induced changes in motion affect the oscillation characteristics of an OWC. As the collector of the OWC wave energy converter is inclined, the direction of motion of the water column is also inclined because it is constrained by collector walls. To investigate this idea, we developed a mechanical 1-degree-of-freedom oscillator model of an inclined OWC. The usefulness of the mechanical model was confirmed in a water tank test with OWCs inclined at 90° (vertical), 45°, and 18.4°. We then investigated the effect of inclination on the resonance period and the optimum power take-off damping of the OWC. The resonance period was mainly prolonged by the reduced restoring force as the motion direction changed. The optimum power take-off damping of an inclined OWC equaled the radiation damping, as observed in vertical OWCs. Finally, we varied the air chamber volume and observed much smaller effects than when varying the inclination. We conclude that changing the direction of motion affects the oscillation characteristics of OWCs mostly because of the reduction of gravity restoring force.

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1. Introduction

The oscillating water column (OWC) wave energy converter is among the most reliable wave energy conversion systems. Many full-scale prototype tests have been performed on floating offshore types (Ishii et al., 1982; Yukihisa et al., 2001) and shoreline fixed types (Hotta et al., 1986; Pecher et al., 2011). At Port Sakata (Suzuki et al., 2004), a shoreline fixed OWC wave energy converter has been continuously tested for 13 years without major accident. In these experiments, a water column oscillating in the vertical motion was constructed as a concrete or steel chamber.

Recently, we conducted the Blow-Hole wave energy converter project in Japan (Miyazaki et al., 2014). In this project, we constructed a cylindrical OWC collector inclined at 18.4° from the horizontal level at the Fukui test site. Unlike standard artificial collectors, our OWC collector is an inclined tunnel drilled into shore rock. As in traditional OWC devices, power take-off equipment with a turbine generator is attached at the top of the tunnel. The other side of the tunnel is a wave inlet. In this type of device, the inclination angle of the OWC is limited by the tunneling cost. Therefore, inclination effects should be properly considered at the preliminary design stage.

Previously, the only inclined OWC wave energy converter subjected to full-scale testing was LIMPET in the United Kingdom. According to the LIMPET report, the inclination of the OWC increases the water surface area and hence the resonance period of the OWC. Moreover, the inlet loss is decreased because of the fluid dynamics. Elsewhere, Ram et al. (2010) experimentally compared the efficiencies of OWCs inclined at angles under limited wave conditions. The DTI project in the UK demonstrated the superior performance of a floating buoy with an inclined OWC and a backward bent duct buoy OWC (Department of Trade and Industry Great Britain, 2004).

However, previous studies appear to lack fundamental physical insight. To elaborate, inclining the OWC changes the direction of motion of the water surface. If the direction of motion is inclined from the vertical axis, the gravitational acceleration slows down, analogous to a box sliding or water falling down a slope. Moreover, if the water is allowed to freely oscillate in the water column, the slower acceleration increases the period of the oscillation, similar to a pendulum swinging on a slope. Thus, the inclination of the OWC might significantly affect the oscillation characteristics of the water column. This type of water motion (with an inclined direction) is pointed to in the literature of oscillating body type wave energy converters (Payne et al., 2008). Therefore, this phenomenon must significantly affect the converter. However, whether inclination changes the oscillation or motion characteristics

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was not considered in previous literature on OWC type wave energy converter.

The collector utilizes the oscillation phenomena of the water column when transferring the power of the wave to the air chamber. Therefore, the power transfer is most effective around the resonance period of the water column. This characteristic has been confirmed in real sea tests (Osawa and Miyazaki, 2004), water tank tests (Sheng and Flannery, 2012), and fluid dynamics simulations (Suzuki, 2005). Alternatively, the oscillations in the water column can be simply and effectively explored by mechanical modeling.

Unlike computational fluid dynamics, mechanical modeling treats the water column as a rigid body, and its motion as a 1-degree-of-freedom (DOF) oscillation. An example (Brendmo, 1997) of a mechanical model that ignores the air compressibility of the air chamber is presented in Fig. 2. Clearly, this model determines the resonance period or optimum power take-off damping without a time series calculation. Although parameters must be properly determined to obtain precise characteristics, the resonance period is obtainable from the mass of the water column m, which is easily computed from the water column geometry (Osawa and Miyazaki, 2005; Webb et al., 2005). Moreover, if we can determine the radiation damping C_1, we can analytically derive the power take-off damping C_2 that maximizes the efficiency. Combined with a nonlinear model of the air chamber, this model can be iterated through a time series at a less computational cost than a fluid dynamics simulation. Thus, mechanical models are useful for obtaining characteristic values such as the resonance period and optimum damping parameters. Recently, such models have been used to investigate air chamber compressibility and turbine characteristics (Folley and Whittaker, 2005) to optimize the damping of a floating OWC (Stappenbelt and Cooper, 2010) and to establish coupled simulation codes of floating OWC wave energy converters (Bayoumi et al., 2014).

The present research investigates how changes in the motion direction affect the water column in an inclined OWC. We first deduce qualitative characteristics by physical analogy to a fluid or rigid body on a slope. We then propose a mechanical model of the inclined OWC that predicts the quantitative characteristics of the system. The appropriateness of the model is validated in water tank tests. The time series, sensitivity of the power take-off damping, and OWC efficiency are determined for different inclination angles. Finally, using the inclined OWC mechanical model, we discuss the fundamental characteristics of the OWC, i.e., the resonance period, optimum power take-off damping, and air compressibility effects.

2. Materials and methods

This research studies the change in the motion or oscillation characteristics of an OWC caused by inclination. Previous studies have focused on the fluid properties, such as inlet resistance, of inclined OWCs. Here, we clarify the effect of inclination on the oscillation characteristics of the OWC using a mechanical model. Section 2.1 presents the details of the model, including the air chamber model discussed in previous literature. Section 2.2 explains the water tank tests for verifying the model and their parameters. Section 2.3 describes the efficiency calculation of the OWC.

2.1. Model of the inclined OWC system

2.1.1. Equation of motion of an inclined water column

In the mechanical model of the inclined OWC (Fig. 1, right), the water column is assumed as a rigid body. The equation of motion of the inclined water column is then given by

$$m(y)\ddot{y}+C_1(\omega)\dot{y}+\rho_w Aygsin\theta = F_1-F_2,$$
$$m(y)=Ay\rho_w+m_0+m_a(\omega), \tag{1}$$

where y is the displacement of the water surface along the direction of motion, $m(y)$ is the mass of the water column, m_0 is the geometrically determined mass of a still water column (i.e., a volume surrounded by inlet, chamber wall, and water surface), and m_a is an additional mass that moves with the water column; C_1 is the radiation damping coefficient, ρ_w is the water density, A is the cross-sectional area of the water column along the direction of motion, and gis the gravitational acceleration; F_1 is the wave exciting force and F_2 is the force from the air chamber pressure; and θ is the inclination angle of the water column from the horizontal level ($\theta=90^\circ$ denotes a vertical water column).

According to Eq. (1), an inclined water column moves along the inclination direction at a specified slope angle and is constrained by the surrounding chamber walls. If the water level increases from the still water level ($y>0$), the water column mass increases by $Ay\rho_w$. The vertical gravitational force on the increased mass is $Ay\rho_w g$. Because the motion is inclined at angle θ, the gravitational force is reduced by $sin\,\theta$ along the y direction. If the water level decreases from the still water level ($y<0$), the mechanics are reversed because the gravitational force acts to restore the still level. As the water level changes, the incoming or outgoing water induces a wave, giving rise to the radiation damping force $C_1(\omega)\dot{y}$, which resists the water column motion.

If $\theta=90^\circ$, the mechanical model reduces to that of the vertical OWC as follows (Kinoshita et al., 1984):

$$m(y)\ddot{y}+C_1(\omega)\dot{y}+\rho_w Ayg = F_1-F_2. \tag{2}$$

Clearly, we cannot retrieve Eq. (1) by tuning any of C_1, m_a, or m_0, i.e., by adjusting the fluid loss or OWC geometry (such as the water surface area and the inlet shape). Therefore, the fluid loss and geometry (which have mainly featured in previous literature) do not completely explain different oscillational phenomena in the inclined and traditional vertical OWCs.

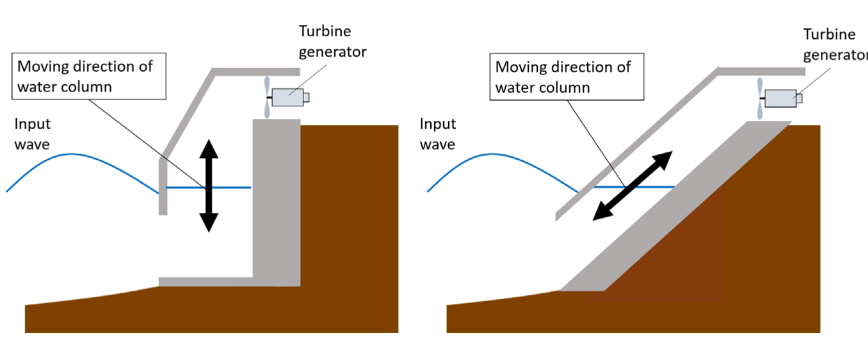

Fig. 1. Vertical OWC (left) and inclined OWC (right).

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