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Research Article

A Wave Energy Extraction System in Experimental Flume

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Ocean wave energy is a high energy density and renewable resource. High power conversion rate is an advantage of linear generators to be the competitive candidates for ocean wave energy extraction system. In this paper, the feasibility of a wave energy extraction system by linear generator has been verified in an experimental flume. Besides, the analytical equations of heaving buoy oscillating in vertical direction are proposed, and the analytical equations are proved conveniently. What is more, the active power output of linear generator of wave energy extraction system in experimental flume is presented. The theoretical analysis and experimental results play a significant role for future wave energy extraction system progress in real ocean waves.

1. Introduction

Access to wave energy in useful forms has been one of the most important investigations for many years. Wave energy, a renewable resource and high energy density, is therefore promoting the development of global economy under the condition of efficient utilization [1]. There are many technical principles reported in papers and conferences on how to convert wave energy into electric power by linear generators [2–4]. Some of these technical principles have been tested in ocean waves, and the test results were proved to be promising as electric power can be obtained directly from wave energy without complex mechanical transmission [5, 6]. Among these technical principles, two methods of wave energy extraction system have been proposed: (1) design generators such as rotating or linear generators to convert the kinetic energy of waves into electric power [7] and (2) considering the rectification and filtration of the electric power from wave energy to grid connected power [8].

Many research studies are focusing on either design generators or electric power conversion to optimise the wave energy extraction system, while few investigate the motion of the heaving buoy, which drives the linear generator to power generation operation. Actually, the operation process of heavy buoy is difficult to describe due to the nonlinear motion of ocean waves.

In this paper, the wave energy extraction system includes a heaving buoy and a linear generator is proposed. Considering the effect of radiated potential, the analytical equations of heaving buoy oscillation in vertical are presented. The wave energy extraction system has been tested in an experimental flume, and the tested results indicate that the method of analytical equations is effective. The theoretical analysis and experimental results play a significant role for future wave energy extraction system progress in real ocean waves.

2. Theory

2.1. Wave Maker in an Experimental Flume. The wave maker in an experimental flume consists of an oscillating plate at $x = 0$ with water of depth h, as shown in Figure 1. The oscillating plate ($h_1 < z < h_2$) is able to oscillate in horizontal direction. When the oscillating plate oscillates in horizontal direction, a complex amplitude radiated velocity potential $\widehat{\varphi}_r$ is generated, which can be defined as

$$\widehat{\varphi}_r = \varphi_z \widehat{v}_1, \tag{1}$$

where φ_z is a coefficient of proportionality and $\widehat{v}_1$ is complex amplitude velocity of oscillating plate [9].

In terms of a wave propagation in the positive x direction and towards $x = \infty$ under the circumstance of a given

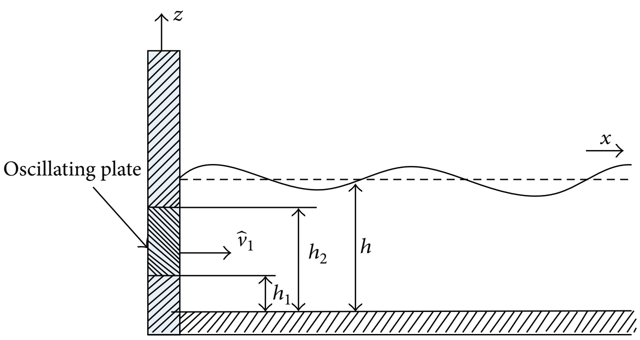

Figure 1: Cross section of the experimental flume.

oscillating plate at $x = 0$, it is easy to write down the Laplace equation (2) and the boundary conditions (3) and (4):

$$\nabla^2 \varphi_z = 0, \tag{2}$$

$$\left[\frac{\partial \varphi_z}{\partial z}\right]_{z=-h} = 0, \tag{3}$$

$$\left[-\omega^2 \varphi_z + g\frac{\partial \varphi_z}{\partial z}\right]_{z=0} = 0. \tag{4}$$

In the above equations, ω is the angular frequency and g is the acceleration of gravity. Due to (2), (3), and (4), we can also write down the following solution of the boundary-value problem which satisfies the region of $x > 0$ and the radiation condition at $x = \infty$ [10]:

$$\begin{aligned} \varphi_z &= c_0 \exp(ikx) Z_0(z) + \sum_{n=1}^{\infty} c_n \exp(m_n x) Z_n(z) \\ &= \sum_{n=0}^{\infty} X_n(x) Z_n(z). \end{aligned} \tag{5}$$

Equation (5) resulted from the method of variable separation; $Z_n(z)$ is an orthogonal function. k is the wave number and m_n is real. In (5), $n \geq 1$ represents evanescent waves which can be negligibly near $x = 0$. Thus in the region of $0 < x < \pi/h$, it can be assumed that

$$\varphi_z = c_0 \exp(ikx) Z_0(z). \tag{6}$$

2.2. Motion Equation of Heaving Buoy. As shown in Figure 2, the heaving buoy's water plane area is S_{wp}, submerged volume is V_p (volume of displaced water), wet surface is S with unit normal $\vec{n}$, and the vertical unit vector is $\vec{n}_z$. According to the linearised theory and potential theory of waves in the experimental flume, the velocity potential $\hat{\phi}$ can be expressed as

$$\hat{\phi} = \hat{\phi}_0 + \hat{\phi}_d + \hat{\phi}_r, \tag{7}$$

where $\hat{\phi}_0$ is incident potential, $\hat{\phi}_d$ is diffracted potential, and $\hat{\phi}_r$ is radiated potential.

It is assumed that only an incident wave exists and a heaving buoy is restricted to oscillation in the vertical only. The heaving buoy was subject to three forces, namely, the vertical wave force $\hat{F}_z$, the radiation force $\hat{F}_r$, and the hydrostatic buoyancy force $\hat{F}_b$, which can be written as follows:

$$\begin{aligned} \hat{F}_z &= i\omega\rho \iint_S \left(\hat{\phi}_0 + \hat{\phi}_d\right) \vec{n}_z dS, \\ \hat{F}_r &= \left(\omega^2 m_z - i\omega R_z\right) S, \\ \hat{F}_b &= -\rho g S_{\mathrm{wp}} S, \end{aligned} \tag{8}$$

where m_z is the added masses of heaving buoy and R_z is the damping coefficient of heaving buoy.

Furthermore, there may be some other additional forces acting on the heaving buoy, such as the viscous force $\hat{F}_v$ and the friction force $\hat{F}_f$. According to Newton's law, the term of motion equation for the heaving buoy oscillation in vertical may be written as

$$\begin{aligned} m_m \hat{a}_z &= \hat{F}_z + \hat{F}_r + \hat{F}_b + \hat{F}_f, \\ \hat{F}_v &= -i\omega R_v \hat{s}_z, \\ \hat{F}_f &= -i\omega R_f \hat{s}_z, \end{aligned} \tag{9}$$

where m_m is the weight of heaving buoy, $\hat{a}_z$ is the acceleration of moving parts, $\hat{s}_z$ is the heaving buoy position, and R_f is the friction resistance from linear generator.

According to $\hat{a}_z = i\omega\hat{v}_z = -\omega^2\hat{s}_z$, the velocity and position of heaving buoy in the vertical direction can be written as

$$\begin{aligned} \hat{s}_z &= \frac{\hat{F}_z}{-\omega^2\left[m_m + m_z\right] + i\omega\left[R_v + R_f + R_z\right] + \rho g S_{\mathrm{wp}}}, \\ \hat{v}_z &= \frac{\hat{F}_z}{i\omega\left[m_m + m_z\right] + R_v + R_f + R_z + \rho g S_{\mathrm{wp}}/i\omega}. \end{aligned} \tag{10}$$

2.3. Wave Energy Absorption by Heaving Buoy. The utilization of wave energy converting into electric energy is still in an initial state of technological development. This section focuses on wave energy absorption by a heaving buoy oscillating in the vertical direction only. The heaving buoy oscillates with a velocity $\hat{v}_z$ mainly due to vertical wave force $\hat{F}_z$ produced by an incident wave. According to [9], the power absorption can be manifested as follows:

$$P = P_e - P_r, \tag{11}$$

where

$$P_e = \frac{1}{2}\left|\hat{F}_z\right| \cdot \left|\hat{v}_z\right| \cos(\theta) \tag{12}$$

is the wave power from the incident wave in heave and

$$P_r = \frac{1}{2}\left|R_z\right| \cdot \left|\hat{v}_z\right|^2 \tag{13}$$

is the radiated power caused by the heaving buoy. Here θ is the phase difference between $\hat{F}_z$ and $\hat{v}_z$, and R_z is the radiation resistance.

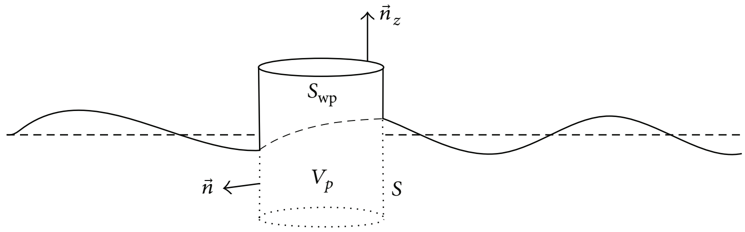

Figure 2: Heaving buoy in waves.

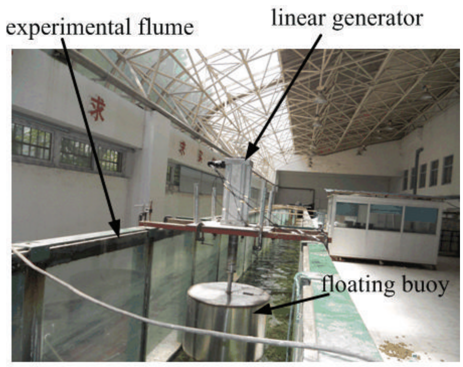

Figure 3: The wave energy extraction system in an experimental flume.

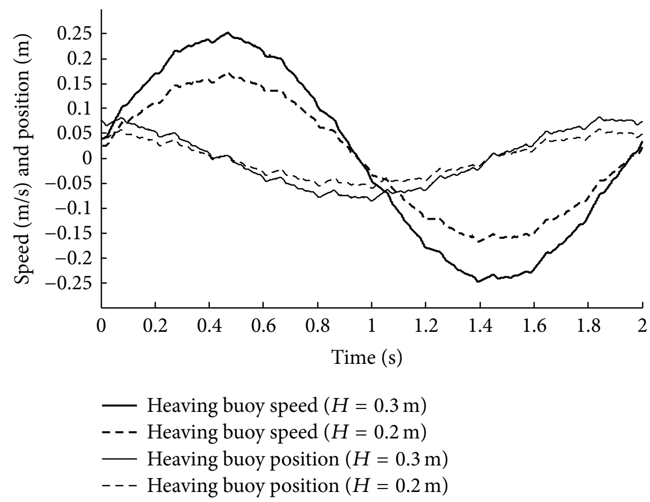

Figure 4: Position and speed of the heaving buoy in the vertical direction according to different wave height [H]; the wave period is 2 s.

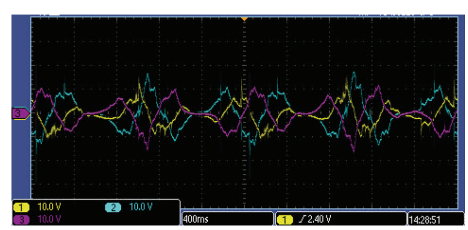

Figure 5: The measured no-load voltage of wave energy extraction system.

3. Experimental Results

For the purpose of verifying that the theory analysis is feasible, a wave energy extraction system is constructed in an experimental flume. The wave energy extraction system includes a three-phase permanent magnet linear generator and a heaving buoy, as illustrated in Figure 3.

In experiment, the wave maker in experimental flume could provide wave height 0.2~0.3 m and wave period 1.6~2.2 s. Concerning the cogging force of linear generator, from Figure 4 and (10) it is concluded that the more the wave height (wave period is constant 2 s), the more the heaving buoy position and the speed in vertical.

Figure 5 shows measured three-phase no-load voltages from the three-phase linear generator of wave energy extraction system. In Figure 5, the wave of three-phase no-load voltages is burr, which indicates that some voltage filter and rectifier system is needed before the power energy is ultimately used.

Active power of three-phase linear generator of wave energy extraction system under incident wave power, radiated wave power, and floating buoy absorbed power for one buoy stroke is presented in Figure 6. As seen from Figures 4 and 6, the active power, incident wave power, radiated wave power, and floating buoy absorbed power are zero corresponding to the upper and lower buoy positions, where the buoy speed is zero. In case of harmonic time variation, the speed of linear generator is not constant; therefore the active power of linear generator of wave energy extraction system is also not constant.

4. Conclusions

Analytical equations of a heaving buoy oscillation in the vertical direction and a three-phase linear generator have been proposed for wave energy extraction system in this paper. The feasibility of analytical equations is proved, and experimental results indicate a possibility to extract electric power from wave power directly by three-phase linear generator. In the experimental results, the curves of three phase no-load voltages are burr, and the speed of linear generator is not constant. Therefore, some methods are needed to optimise the properties of linear generator, and an optimal control method is also needed to improve the operation process of wave energy extraction system.

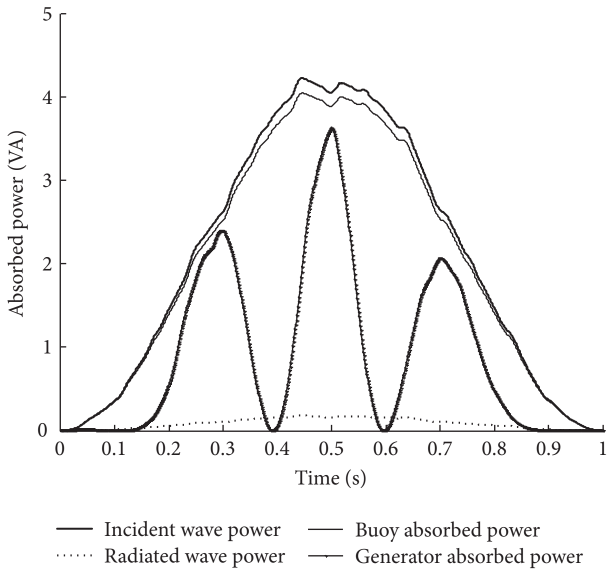

FIGURE 6: The heaving buoy absorbed power, incident wave power, radiated wave power, and active power of linear generator for one buoy stroke.

Competing Interests

The authors declared that they have no conflict of interests regarding the publication of this paper.

Acknowledgments

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