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Design and analysis of wave energy converter for a buoy

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Abstract

This paper introduces the design method for the practical use of a wave energy converter (WEC), and the associated results are application to the commercially available WEC for buoys. Peak performance of WEC occurs at resonance with driving waves. This type of resonance occurs when one of the parameters in an oscillator varies periodically. The water column in a WEC oscillates under the effect of gravity and the compression of an air chamber. The analysis of WEC is developed by assuming independence of the buoy heaving motion and the motion of the water column within the center cylinder. Results of analysis are then compared with simulation data, and applied to designing a WEC for buoys. Also, the effect of the various parameters such as cylinder length, period, mass and wave height is analyzed for the optimum design of a WEC. Finally, the research results are applied to a wave simulator with operating LabView, and some ideas are presented to the design method of WEC for buoy with simulation experiment.

Keywords: WEC(Wave Energy Converter); Buoy; Resonance; Water column; Optimum design

1. Introduction

Ocean waves are mathematically complex; consequently, their complete description requires several parameters. A sea state is conventionally represented by a scatter diagram showing the number of waves occurring at each height and period.

Such detailed statistics are important for the design of individual wave energy converters. However, for the purpose of a broad resource assessment, wave height is the most important parameter. Waves are commonly characterized by the significant wave height, which is the mean height of the highest one third of the waves and is also reported to coincide with visual assessments of wave height.

To supply power to several buoys, several countries have utilized a wave energy converter (WEC). The device utilizes the relative air motion above an internal free-surface to drive a turbo-generator as wells turbine generator. The air is excited by both the heaving motions of the buoy and the motions of the internal free-surface which is in free communication with the sea. In the design of the WEC, the most significant item is that an optimum length of the internal water column exists, i.e., a length for which maximum power is converted near the heaving resonance. This paper describes the influence of internal water column length on the converted kinetic energy of the wave. Further, the wave height effect on the energy conversion is also studied.

The purpose of this paper is to perform a theoretical analysis of the WEC and design the optimum WEC for a buoy system. Also, some basic concepts are explored as a possible way of improving the performance of WEC systems with a simulator. Finally, this

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paper's results are applied to a hybrid system for a buoy.

2. Principle and theory for WEC

One of the main problems with WEC for a buoy is to establish a reference. The most obvious reference for WEC is a strut connected to the ocean floor, a fixed reference or mooring system. The WEC can be slack-moored, and the mooring with spring is used to keep the WEC in the desired horizontal position.

It is essential that WEC is provided for optimum control of the oscillatory motion, in order to achieve maximum power conversion. In an oscillator as WEC, the normal modes of oscillation are a function of several parameters, such as the mass, spring constant and heaving motion.

When one of these parameters changes periodically, a small perturbation can grow exponentially in time. In this type of resonance, energy is transferred with much greater efficiency than in ordinary resonance.

The purpose of the experimental investigation is to design a WEC simulator. Fig. 1 is a schematic diagram of the WEC for a buoy.

In Fig 1, WEC has to be analyzed with water column motion, momentum within the turbine passage, heaving motion of the buoy and power relationship.

The air velocity of the internal free-surface is then

$$\dot{\xi}_1 = -\frac{\omega \bar{H}_i}{2}\sin(\omega t) \tag{1}$$

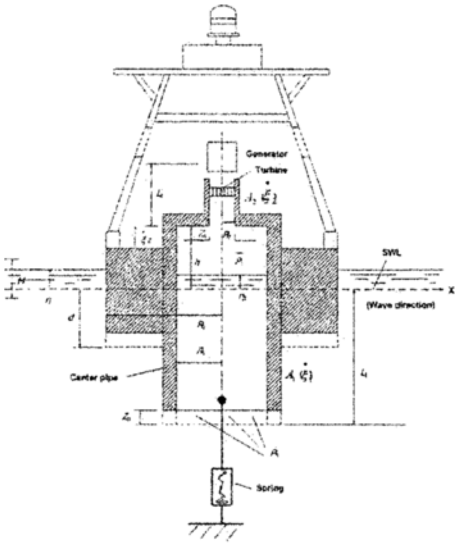

Fig. 1. Schematic diagram of the WEC for buoy.

Where $\bar{H}_i$ is the spatially averaged internal wave height. ω is the circular wave frequency. Since air is incompressible, the axial velocity in the turbine passage is

$$\dot{\xi}_2 = -\frac{A_1}{A_2}\frac{\omega \bar{H}_i}{2}\sin(\omega t) \tag{2}$$

Thus, the relative unsteady air velocity in the turbine passage is

$$\dot{\xi}_2 = \dot{\xi}_1\,(D_1/D_2)^2 \tag{3}$$

Where D_1 and D_2 are the inner diameter and turbine passage diameter of the axis symmetry float, respectively. The data in Fig. 2 show the behavior of ξ_1 with time, while keeping the wave height H. From the results in that figure one can see that the air velocity is changed with H.

From Fig. 3, the internal velocity in the turbine pas-

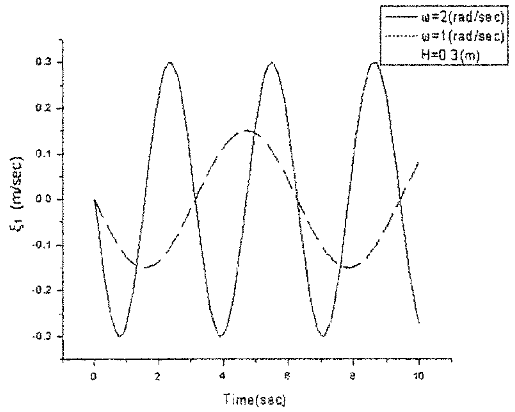

Fig. 2. Air velocity of the internal free-surface.

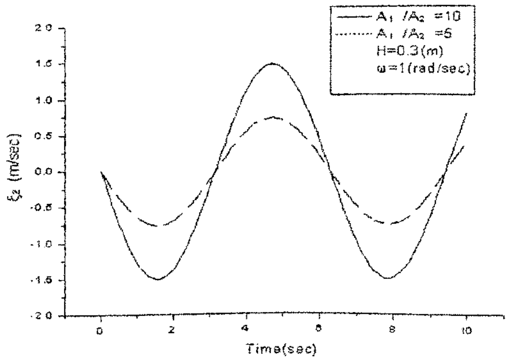

Fig. 3. Axial velocity in the turbine passage.

sage becomes higher in proportion to the area rate of air flow.

The momentum within the turbine passage is described by the equation

$$A_1\xi = A_1(\eta_{1a} - z_b) = A_2(\eta_t - z_b) \tag{4}$$

Where ξ is the relative air displacement within the center column. The turbine area A_2 is much smaller than the water column area A_1; the turbine passage velocity $\dot{\xi}_2$ is much great than $\dot{\xi}_1$. η_t is the displacement of the air from the equilibrium position at the exhaust, z_b is the heaving displacement of the buoy.

The chamber pressure p_1 can be modified with Bernoulli's equation as equation (5).

$$p_1 = -\rho_w(L_1 + \xi)\ddot{\xi} \tag{5}$$

Where ρ_w is the mass density of saltwater, and L_1 is the still water length of the inter water column. The power P_{out} available to the turbine depends on the pressure gradient and volume rate of airflow Q_{out} across the turbine:

$$P_{out} = (p_2 - p_0) = Q_{out} \tag{6}$$

For simplicity, the exhaust pressure p_0 is assumed to be ambient. The upstream pressure p_2 is related to the pressure within the air chamber by the energy equation due to Bernoulli,

$$p_2 = p_1 + \frac{1}{2}\rho_w(\dot{\xi}_1^2 - \dot{\xi}_2^2) + \rho_w\frac{\partial}{\partial t}(\varphi_1 - \varphi_2) \tag{7}$$

The velocity potentials, φ_1 and φ_2, are given by:

$$\varphi_1 = -\frac{\omega H_i^2}{4}\sin(\omega t)\cos(\omega t) \tag{8}$$

$$\varphi_2 \cong \frac{A_1}{A_2}\varphi_1 \tag{9}$$

3. Design foundation

If the wavelength λ is smaller than the characteristic length of cross section of the water column, then an odd or even number of waves can occur within the water column. When the number of waves is even, the integrated power output is zero. If the number is odd, a peak occurs in the power curve. When λ is greater than the characteristic length, the power is obtained from a single wave.

The cavity resonance technique is used in some commercially available buoys to power navigation aids such as lights and horns. If designed properly, this application can take advantage not only of the cavity resonance, but also of the heaving motion of the buoy.

The turbine passage velocity can be exploited by placing a wells turbine to convert the kinetic energy of the air into electrical energy. In the design of a wave energy conversion device, therefore, our goal is to minimize the damping to obtain the maximum response.

In Fig.1 $\dot{\xi}_2$ can be expected to have two relative maxima, one at the cavity resonance frequency of equation (10) and the other at the heaving resonance frequency of equation(11). The natural frequency of the internal water column motion is

$$\omega_c = (g/L_1)^{1/2} = 2\pi/T_c \tag{10}$$

Also, the heaving resonant frequency is

$$\omega_z = \sqrt{c/(m + m_w)} = 2\pi/T_z \tag{11}$$

Where m and m_w are the buoy mass and added mass. m_w is the mass of the excited by the heaving motion. The heaving motions of the buoy are described with the damping coefficient, restoring coefficient, buoy mass, added mass, dynamic pressure and the mass density of the air. The restoring coefficient, c, is

$$c = \rho_w g(D_0^2 - D_1^2)\pi/4 = \rho_w g A_{wp} \tag{12}$$

Where ρ_w is the mass density of the water, and g is the gravitational constant, D_0 is the outer diameter of the axis symmetry float, and A_{wp} is the water plane area.

By using these resonance conditions, we can now see that the design condition is

$$\omega_c = \omega_z \tag{13}$$

The peak power values are affected by the system damping such that as the damping increases the power decreases. In the buoy system, the damping is due to the creation of waves by both the heaving motion of the buoy and the vertical motion of the water column.

In addition, friction on the wetted body surfaces and friction and turbulence losses in the airflow add to the damping. To optimize the design of the buoy system, we use the design condition given in equation (13). Equation (13) can be written as

$$g/(L_1 + L_1') = -c/(m + m_\omega) \tag{14}$$

Where L_1' is an effective length due to the added mass excited by the water column. The design condition, $T_c = T_z$, is obtained from equation (14). We choose T_c to be the design period. We keep the dimensions in equation (14) the some as originally used and simply change the mass 'm' of the system by adding ballast. m_ω is the added mass, that is, the mass of the water excited by the heaving motion. m_ω is a function of geometry and will slightly change with the additional draft d. The added mass, m_ω, excited by the heaving circular floatation body is

$$m_\omega = C_e \rho_w \pi (R_0 - R_1)^3 \tag{15}$$

Where C_e is a numerical coefficient corresponding to the buoy geometry. The draft of float is

$$d = m/(\rho_w A_{wp}) \tag{16}$$

The draft of float in Fig. 5 varies with Awp. The water plane area is defined by the outer diameter and inner diameter.

The air flux, Q_c, is defined by

$$Q_c = \int_0^{D_1} \eta_{1a} dl \tag{17}$$

Generally, Q_c increases slightly with increasing values of D_1 in Fig. 5.

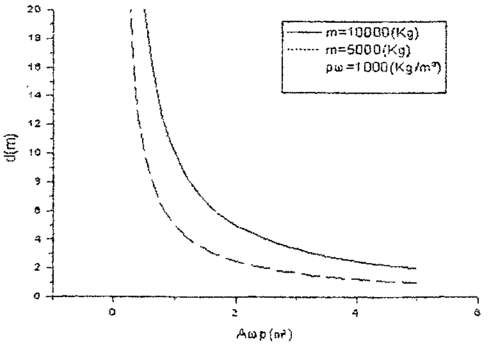

Fig. 4. Draft variation with water plane area.

The heaving resonance value of the maximum value of the relative air velocity in the turbine passage is seen to increase slightly with increasing values of L_1.

4. Experiment and analysis

The power available to double acting turbine from air flow was obtained by applying equation (7). For

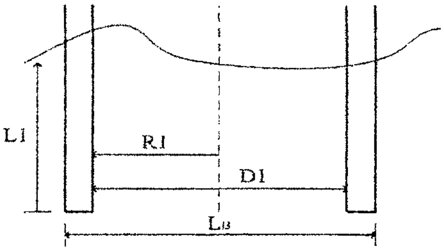

Fig. 5. WEC chamber.

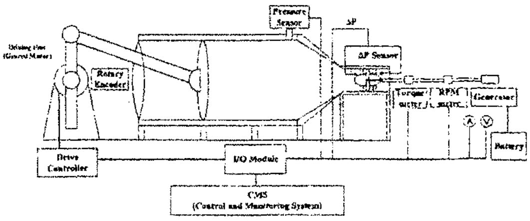

Fig. 6. Schematic diagram of Simulator for WEC.

Table 1. Simulator properties.

Items	Specifications
Main Base	L3,345 x b800 x h1,050mm / Ss square bar
Air duct	Id754 x l1000mm / Pp plate
Air com	Id754 x id230 x l408mm / Pp plate
Air piston	Od752mm / Pp plate with crank mechanism
Control System	Period control : 0~110rpm Wave height control : 200~800mm Driving unit : geared motor
Turbine Duct	Id230 x l600 x 10t / Transparency acryl
Air turbine	Type : wells turbine Blade section : naca 0020 / 6-blades Material : al & abs resin
Generator	12vdc, 100w, bldc motor(hmeb-074)
Rpm meter	Max. 20,000rpm
Battery	2v 400ah × 3

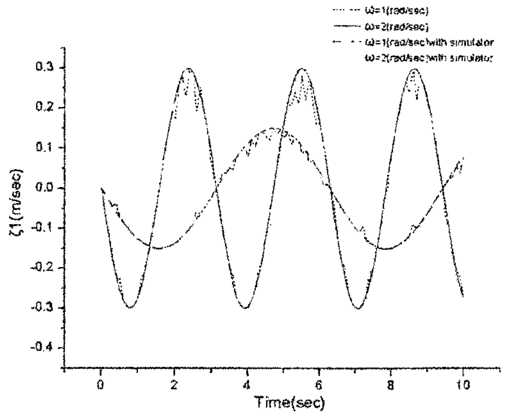

Fig. 7. The result of air velocity with equation and simulator.

Table 2. Characteristic of sensors.

ITEMS	RANGE	OUTPUT
Pressure sensor	-760 mmHg ~ -2 bar	4~20 mA
Torque meter	5-100(kgf-cm)	1 mV/V
Torque meter amplifier	Maximum indicator 3267	0-10 V (4-20 mA)
Different Pressure Transmitter	0~30 (mbar)	4~20 mA
Encoder	3600 (pulse/rotation)	0-24 V

the confidence of design theory for WEC, the simulator is constructed as in Fig. 6.

The basic properties of the buoy simulator are illustrated in Table 1.

The simulator can control the wave frequency by the motor rpm and water column length. The motor rpm is controlled from 0 to 110 with an inverter, and this simulator adjusts the stroke from 20cm to 80cm for testing of wave height influence. The generating power is changed from 0 to 100 W.

Fig. 7 shows the simulation results of air velocity with simulator From Fig. 7 the simulation data are followed with equation (1) in Fig. 2. Table 2 presents the sensors characteristics for a simulator

The characteristics of volt, torque and power of simulator are presented in Fig. 8.

The oscillating water column period is matched to the rpm of the simulator, and the properties of the buoy simulator in Fig. 8 are approached in the research purpose.

Fig. 9 shows the results for the effect of water column with the period T. The generating power as pre dicted by the theory is seen to increase with increasing values of water column height and decrease with increasing values of oscillating water column period T.

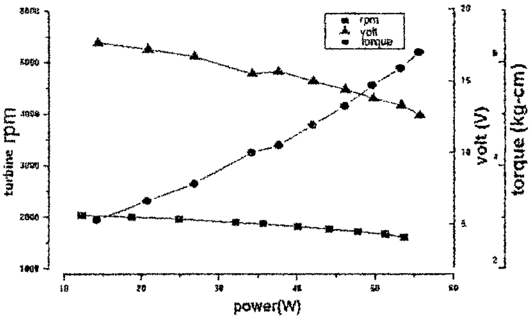

Fig. 8. Characteristics of simulator.

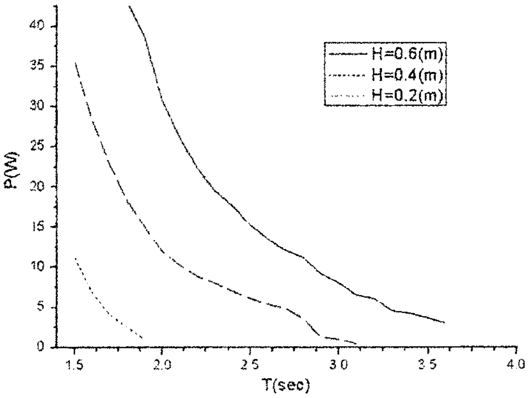

Fig. 9. Generating power with the water column period variation.

The energy conversion efficiency of a cavity resonance system ultimately depends on the turbine design. The turbine efficiency will be presented in the next paper.

5. Conclusion

From the data presented herein, one can conclude that the generation power is proportional to the wave height, and is an inversely proportional to the water column period. WEC is most effective for waves near the resonant period of the buoy and water column system. From the theory and simulation data presented in this paper, we can see that the characteristics of buoy are related to the variation of each parameter. Furthermore, by conducting such an experiment, we confirmed the generation of power with a period and height of the oscillating water column.

In the future, a WEC for a buoy will be designed with this paper's results, and we will test the performance of WEC in the sea.

Acknowledgments

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Nomenclature

η_1 : Internal free-surface displacement, m
A_1 : Cross-sectional area of the water column, m^2
A_2 : Cross-sectional area of the turbine, m^2
A_{wp} : Water plane area, m^2
C : Restoring coefficient
C_e : Numerical coefficient
D_1 : Inner diameter of buoy, m
D_2 : Turbine passage diameter, m
d : Draft of float, m
g : Gravitational constant, m/sec^2
$\overline{H}_r$: Spatially averaged internal wave height, m
L_1 : Still water length of the inter water column, m
m : Buoy mass, kg
m_w : Added mass, kg
p_0 : Exhaust pressure, pa
p_1 : Chamber pressure, pa
p_2 : Upstream pressure, pa
Q_c : Air flux, kg/m^3
T_{eff} : Efficiency of turbine, %
z_b : Heaving displacement of the buoy, m
ω : Circular wave frequency, rad/sec
$\dot{\xi}_1$: Air velocity of the internal free-surface, m/sec
$\dot{\xi}_2$: Air velocity in the turbine passage, m/sec
ρ_w : Mass density of saltwater, kg/m^3
φ : Velocity potential, m^2/sec
ω_c : Natural frequency of the internal water column
ω_z : Heaving resonant frequency, rad/sec

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