Journal of Navigation and Port Research International Edition
Vol.32, No.9 pp. 705~709, 2008 (ISSN-1598-5725)

Analysis and Design of a Wave Energy Conversion Buoy

Jin-Seok Oh† · *Soo-Young Bae** · *Sung-Young Jung***

† *Professor, Division of Mechatronics Engineering, Korea Maritime University, Busan 606-791, Republic. of Korea*
*, ***Graduate School of Korea Maritime University, Busan 606-791, Republic. of Korea*

Abstract : *In the sea various methods have been conducted to capture wave energy which include the use of pendulums, pneumatic devices, etc. Floating devices, such as a cavity resonance device take advantages of both the water motion and the wave induced motions of the floating body itself. The wave energy converter is known commercially as the WAGB(Wave Activated Generator Buoy) and is used in some commercially available buoys to power navigation aids such as lights and horns. This wave energy converter consists of a circular flotation body which contains a vertical water column that has free communication with the sea. A theoretical analysis of this power generated by a pneumatic type wave energy converter is performed and the results obtained from the analysis are used for a real wave energy converter buoy. This paper is shown to have an optimum value for which maximum power is obtained at a given resonant wave period. Also, the length of the internal water column corresponds to that of the water mass in the water column. If designed properly, wave energy converter can take advantage not only of the cavity resonance, but also of the heaving motion of the buoy. Finally, simulation is performed with a LabVIEW program and the simulation results are applied to a wave energy simulator for modifying design data for a wave energy converter.*

Key words : *Wave, Energy, Converter, Resonance*

1. Introduction

In this paper, our interest is forced on the basic mathematical description of water wave and the analysis of air flow and motions for a wave power generation system. Also, this paper suggests a power increment method of WEC(wave energy converter) with system modifications.

In a random sea, the WEC is subjected to waves of varying heights and periods. The increased buoyant force due to crest is canceled by the decreased buoyancy due to the trough.

It is essential that the WEC is provided for optimum control of the oscillatory motion, in order to achieve maximum power conversion. In an oscillator WEC, normal modes of oscillation are a function of several parameters, such as the mass, wave height, period, 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 a much greater efficiency than in ordinary resonance. Fig. 1 shows schematic diagram of the WEC buoy. The WEC buoy consists of a circular floating body which contains a vertical water column that has free communication with the sea. The air above the internal free surface has a relative motion to the buoy caused by both the moving water surface and the heaving of the buoy. The mechanism utilizes the relative air motion above an internal free-surface to drive a turbine for generator.

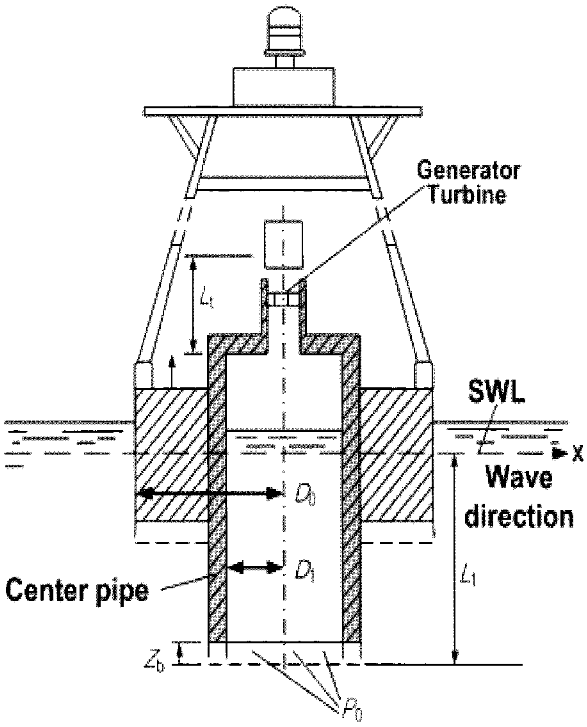


Fig. 1 Schematic diagram of the WEC for buoy

The power converting technique is explained with the

---

† Corresponding author : Jin-Seok Oh, ojs@hhu.ac.kr 051)410-4283
* waterverz@nate.com, (051)410-4866
** whswo85@nate.com, (051)410-4866

heaving resonance characteristic. This paper describes that an optimum length of the internal water column exists, i.e. a length for which maximum power is converted near the heaving resonance. Generally, this type of WEC is installed the navigation aids like buoy for ocean traffic system (McCorimick, 1981; Hong et al., 2004; Korde, 2007).

2. WEC Design for buoy

For design the top priority is the set of parameters such as the added-mass, total effective heaving mass of the buoy, and linear damping coefficients. The peak power of WEC occurs at a resonant period, and the second relative peak power value occurs at the natural period of the buoy water column system (McCormick, 1974; 1976). For the ideal case of no internal resistance in the water column, air chamber, or turbine passage, the resonant period is approximately given the inviscid equation (1).

$$T=2\pi(L_1/g)^{\frac{1}{2}} \tag{1}$$

One would naturally draw the conclusion that an increase in L_1 would result in an increase in the power obtained from the waves. The wave height H has a most significant effect on the maximum power values. It is known that the energy in a wave is proportional to H^2, and the power derived from wave is a product of the energy and fluid velocity. Also, the power W is proportional to square of the wave height. The relative peak values occur at approximately the heaving period of the buoy like the low period peak and at the surge chamber resonance of the water column like the high period peak. The relative low period peak values appear to increase with the water column length.

The mass with water column length increases by the pipe material and the water mass. The optimum design of the buoy is such that the water mass in the center pipe is approximately 2/3 of the buoy mass and the added mass combined. The additional water mass m_w is presented as a function of L_1(McCormick, et al., 1975; McCormick, 1976). The relationship between m_w and L_1 approximately appears to be linear. m_w and L_1 is defined as follow:

$$m_w=6.67\times10^{-4}L_1^2 \tag{2}$$

If the mass was unchanged, the peak power would increase indefinitely with L_1. The increase in mass, however, will limit the power increase and, therefore, there should be a particular value of L_1 which is optimum. The design mass value of body is given by

$$m=\frac{\pi}{4}(D_0^2-D_1^2)\rho_w L_1-6.67\times10^{-4}L_1^2 \tag{3}$$

Where D_0 is the outer diameter of the float, D_1 is the inner diameter.

We keep the dimensions in equation (4) the same as originally used and simply change the mass " m " of system by adding ballast (Thakker et al., 2004). If designed properly, this application can take advantage of not only of the cavity resonance, but also of the heaving motion of the buoy. By using the resonance conditions, we can extract that the design conditions is

$$L_1+L_1'=\frac{4(m+m_w)}{\rho\pi(D_0^2-D_1^2)} \tag{4}$$

Where L_1' is an effective length due to the added mass excited by the water column. To optimize the design of this buoy system, use the design condition given in equation (4). The added mass "m_w" is a function of geometry and will slightly change with the additional draft "d". The draft "d" of the floater is

$$d=\frac{4m}{\rho_w(D_0^2-D_1^2)} \tag{5}$$

A peak power in WEC is changed with the water column length L_1. To determine L_1, a derivative with respect to peak power is set to zero in equation (6).

$$\frac{dW}{dt}=\rho_a\dot{\xi}\pi(D_1/2)^2g\left\{\frac{-\rho_w}{r_a}(L_1+\xi)\ddot{\xi}+\frac{1}{g}\xi\ddot{\xi}\right\} \tag{6}$$

Where W is the power available to the turbine, ρ_a is the air density, r_a is the specific weight of air. The L_1 variation, therefore, can be attributed to the variation of the mass ratio. $\dot{\xi}$ is the difference of the average internal free surface displacement and heaving displacement.

3. Prototype design and simulation

A peak power is changed with the water column length L_1. For determining the peak power condition, a derivative with respect to L_1 in the peak power is set to zero with the ideal situation of zero internal resistance.

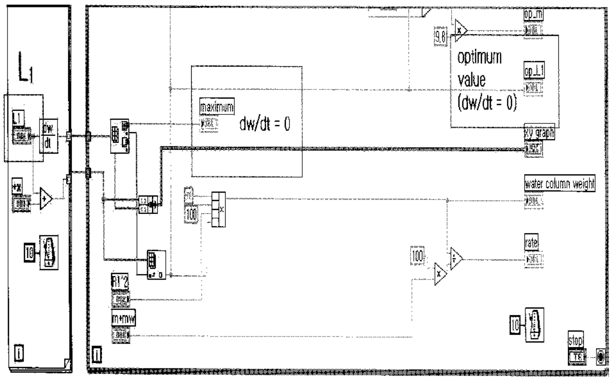
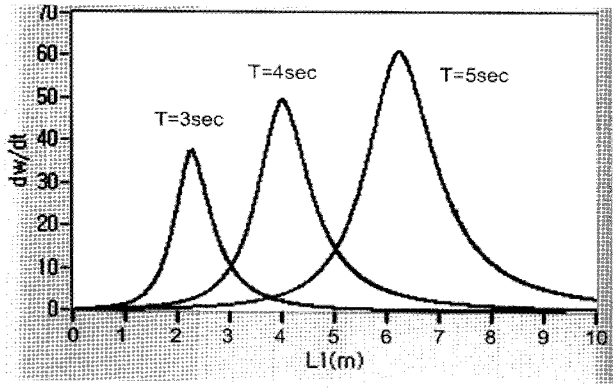


Fig. 2 Block diagram of peak power variation simulation with the water column length

In Fig. 3 the effect of the variation of the water column length L_1 on the peak power is presented.



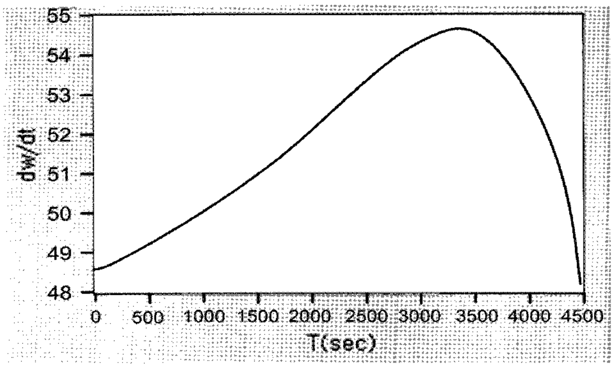
T : wave period

Fig. 3 Peak power variation with the water column length

The peak power occurs when $L_1 \cong 4m$(T=4sec). From equation (3) the water column length variation can be influenced to the variation of the mass.

The mass of the WEC buoy system increases in two ways with increasing the water column length L_1. First, there is the obvious increase in the water column material. Second, there is an increase in the water mass affected. If the mass was unchanged, the peak power would increase indefinitely with L_1. The increase in mass in Fig.4, however, will limit the power increase and, therefore, there should be a particular value of L_1 which is optimum. For lengths greater than this optimum value, the power will be reduced. The actual peak power occurs at a mass 3,180 kg with the water column length 2.9 m.

The block diagram of peak power variation simulation with the wave height is shown in Fig. 5(a). The peak power variation with the wave height is shown in Fig. 5(b). For this purpose both the water column 3m and 4m length are tested for comparison.

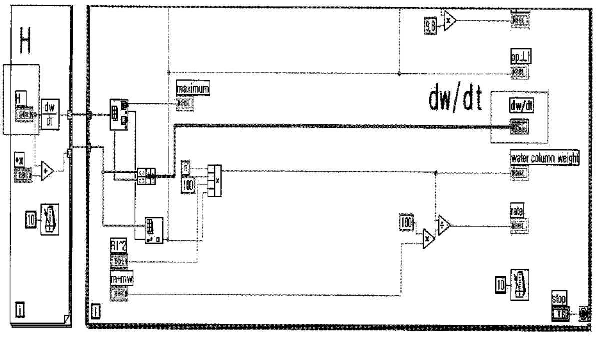


Condition: Water column mass = 2,100 kg

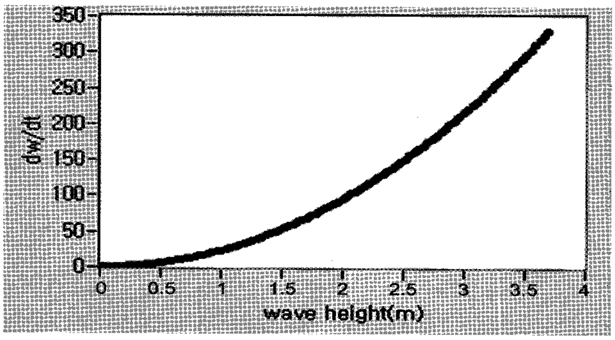
Fig. 4 Peak power variation with the water column mass

The maximum power values occur at different periods for these two lengths since the natural frequency of the water column and buoy system changes with length. The wave energy conversion buoy is most effective in a narrow period band about the damped natural period of the buoy-water column system. From Fig. 5(b) one sees that the wave height has a most significant effect on the maximum power values. The reason is that the power is proportional to the square of the wave height.

Fig.5(c) shows peak power variation with circular wave frequency. From equation (1), when L_1 = 3m, the peak power in the ideal case occurs at a resonant period of 3.418 sec (ω =1.839rad/sec). The second relative peak power occurs at the natural period of the water column. The difference in the real and ideal values is due to the air resistance. The internal free surface motion is very small at the lower peak. Thus, the power generated at the low period peak is primarily due to the heaving motion of the buoy. For longer waves with long period, the heaving motions of the buoy are small, and the particle motion at the bottom of the water column is relatively large. When the wave length λ is equal to the inner diameter of water column D_1, assuming a sinusoidal wave profile, no heaving motion will occur since both a crest and a trough of the wave occur simultaneously over the body length. Furthermore, the increased buoyant force due to a crest is canceled by the decreased buoyancy due to trough, and there is no net vertical force on buoy. Conversely, when an extra trough or crest occurs over the inner diameter D_1, then there is a net vertical force. Heaving can be expected when $D_1 = \frac{N\lambda}{2}$ (N=1,3,5..). The wave power converted by the system operating under ideal conditions is given as a function of wave period. If the wave length λ is smaller than the inner diameter D_1, 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 the wave length λ is greater than the inner diameter of water column D_1, the power is obtained from a single wave. The maximum power conversion occurs at a resonant period. For the confidence of design theory for the WEC, the prototype WEC is constructed. The basic properties of are illustrated in table1.

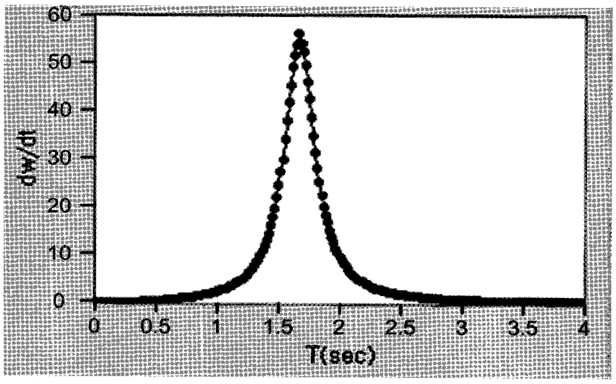


(a) block diagram of peak power variation simulation with wave height



Condition: ωc=ωz(ωc: natural frequency of the internal water column, ωz: heaving resonant frequency)

(b) Peak power variation with wave height



T : wave period, sec

(c) Peak power variation with circular wave frequency

Fig. 5 Peak power variation with wave height and circular wave frequency

Table 1 Specifications of prototype WEC

Item	Specifications	Remark
Water Column length	2.9 m	
Mass of buoy system	3,180 kg	
Weight of generation system	14 Kg	
Generated power	40 W or More	
Minimum wave height	0.5 m	For generation
Water column diameter	1.04 m	Generating condition
Turbine impeller Turbine passage diameter	6 blades 0.25 m	Wells type
Output power	3-phase AC	

In simulation of the prototype WEC, the reliability of design can be verified with the specifications.

4. Conclusion

From the design simulation, one can conclude that the generation power is proportional to the square of 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 related to variation of each parameter. The mass increasing with the water column length will eventually result in optimum length of the water column for which maximum power will be obtained near the heaving resonance period of the buoy.

So, the designer of a wave energy conversion system should first determine which wave period range is of interest, i.e. the low period range surrounding the heaving period of the buoy, of the high period range of the surge chamber resonance. The maximum power values occur at different periods for these two lengths since the natural frequency of the water column and buoy system changes with length. The increase in mass, however, will limit the power increase and, therefore, there should be a particular value the water column length which is optimum. By making conduct an experiment based on simulation, we will try to confirm that of generating power with a period and height of oscillating water column on the sea.

Acknowledgement

This paper is based on ‘a development of hybrid power generation system for ocean facility’ supported by Ministry of Land, Transport and Maritime Affairs of Korea.

References

[1] Hong, D. C., Hong, S. Y. and Hong, S. W.(2004), "Numerical study of the motions and drift force of a floating OWC device", Ocean Eng. Vol.31, pp139-164.

[2] Korde, U. A.(2007), "Efficient primary energy conversion in irregular waves", Ocean Eng. Vol.26, pp625-651.

[3] McCormick, M. E.(1974), "Analysis of a Wave Energy Conversion Bouy", J. Hydronautics, Vol. 8, pp. 77-82.

[4] McCormick, M. E., Bernard, H. C. and Douglas, H. R.(1975), "An Experimental Study of a Wave-Energy Conversion Buoy", MTS journal, Vol. 9, pp. 40-42.

[5] McCormick, M. E.(1976), "A Modified Linear Analysis of a Wave-Energy conversion Buoy", Ocean Eng. Vol.3, pp133-144.

[6] McCorimick, M. E.(1981), "Ocean Wave Energy Conversion", pp. 45-75.

[7] Thakker, A., Usmani, Z. and Dhanasekaran, T. S. (2004), "Effects of turbine damping on performance of an impulse turbine for wave energy conversion under different sea conditions using numerical simulation techniques.", Renewable energy 29, pp. 2133-2151.

Received 2 October 2008
Revised 25 December 2008
Accepted 26 December 2008