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A Study on Wave Power Generation System Utilization of Bell-Mouth Effect to Pairs of Water Chambers

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Abstract: In this study, a research of novel wave power generation system for ocean energy is suggested using bell-mouth effect theory. In wave energy conversion system, it has to be satisfied such as durability, constructability, efficiency in economy and power conversion to certain extent for practical use. These four conditions are met by having a water chamber installed in a series on a breakwater and rotating the hydraulic turbine with the difference in water level from the forward and reverse directions of the Bell Mouth effect. The water transportation model had been designed and put into numerical analysis. According to the analysis, the output power is highest when the wave height is large, the wave cycle short and the water depth deep. The results are to be used later on as reference data to express the change in water level and flux inside the water chamber without inconsistency.

Key words: Hydraulic turbine, water chamber, numerical analysis, wave power generation, inconsistency, economy

INTRODUCTION

A rising demand for energy coupled with the problem of environmental pollution has led to investigations into potential new energy resources (Evans, 1982; Sarpkaya and Lsaacson, 1981; Semsri *et al*., 2016; Attom *et al*., 2016). Wave energy represents one of the most dependable and predictable sources of renewable energy available which is free from the variations present in wind or solar energy. Various mechanisms for extracting wave energy have been developed but not fully realized due to structural strength and economic problems.

A system has to satisfy durability, constructability, efficiency in economy and power conversion to a certain extent for it to be put into practical use. The durability of the device includes those of both the external structure and the power converting portion of the device. It can be said with certainty that the lack of fulfilment of the above mentioned conditions is the main reason that the wave power conversion technology has not reached a commercially generating stage (Nagai *et al*., 2002; Yerzhan and Koshumbaev, 2016; Rodrigues *et al*., 2016).

In order to meet these conditions, Hadano *et al*. (2013, 2014, 2017) designed the system which consists of water chambers array aligned along the wave propagation direction and the float-type wave energy converters each of which is installed in the chamber and utilizes the gentle up/down motion of the water in the chamber. In this system, neither the wall(s) of the chambers nor the energy conversion device(s) are exposed to the impulsive load due to water wave. Waves near the jetty or a loosely moored long floating body will propagate toward the length of these structures. Therefore, an array of water chambers set along the jetty or a long floating structure is profitable in the sense that the outer wall is never exposed to severe wave loads.

The basic principle of energy extraction was proposed earlier. The system consists of multiple water chambers set along the direction of the wave propagation. The motion of the water mass in these chambers is mostly vertical and is utilized for extraction of energy by the rack and pinion system installed in each of the chambers. From this study, the rack and piniondevice in water chambers is to be suitable for wave energy conversion as the float does not move horizontally (Hadano *et al*., 2013, 2014, 2017; Koh *et al*., 2016; Adda *et al*., 2017).

The research presents a power generation system that has water chambers installed in a series on a breakwater which rotates the hydraulic turbine with the difference in water level from the forward and reverse directions of the Bell Mouth effect. The calculations have been made for the mathematical model.

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MATERIALS AND METHODS

Outline of the power generation system and mathematical model

The structure and mechanics of the power generation system: The water chambers are installed in the direction of the water flow, causing it to have forward and revers-direction Bell Mouth effect. This causes one side to have a higher water level than the other which turns the hydraulic turbine in the connecting area, generating electricity. Figure 1 shows the general concept of the power generator. The concept of the hydraulic turbine can be grasped in Fig. 2.

The mathematical model of the power generation system: Let's represent the higher water level chamber as C_h and the lower water level chamber as C_l, the average water sea level height as, $z=\bar{H}$, the water level in C_h as, $z = H_h$ and the water level in C_l as, $z = H_l$. Sea level→Chamber C_h: Q_1, K_{1A}, K_{1B}, Chamber C_h→Chamber C_h Q_2, K_2 Chamber C_l→Sea level: Q_3, K_{3A}, K_{3B}. Furthermore, as K_{1A} and K_{1B} represent each the forward and reverse direction Bell-Mouth effect, respectively, the flux coefficient $K_{1A}>K_{1B}$. Moreover, by defining d as the diameter of the connecting passageway between the chamber, b as the width of the gap between the sea water and the chamber, g as the gravitational acceleration, h, l and s as the mean time value in C_h, C_l and sea level, respectively:

$$Q_2=\frac{\pi d^2}{4}K_2\sqrt{2g(H_h-H_l)} \quad (1)$$

The flux Q_1, Q_3 are decided by the following categories according to the change in sea water level. The flux coefficient is determined by the following equation according to the loss of head ζ:

$$K=\left(1/\left(1+\zeta\right)\right)^{1/2} \quad (2)$$

$$H_s-H_h>0:Q_1 \quad (3)$$

$$H_h-H_s>0:Q_1 \quad (4)$$

$$H_l-H_s>0:Q_3=K_{3A}b\bar{H}_2\sqrt{2g\left(H_l-H_s\right)} \quad (5)$$

$$H_s-H_l>0:Q_3=-K_{3B}b\bar{H}_2\sqrt{2g\left(H_s-H_l\right)} \quad (6)$$

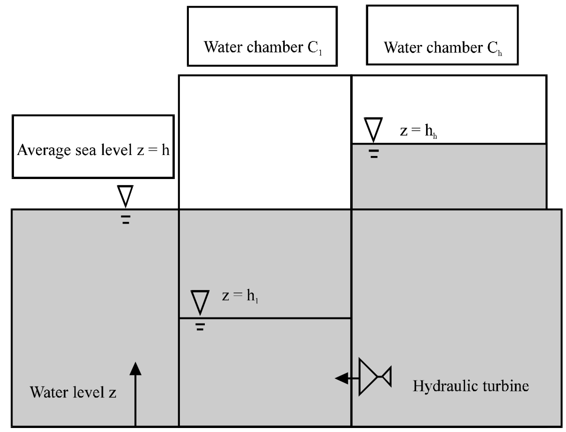

Fig. 1: Concept of this device

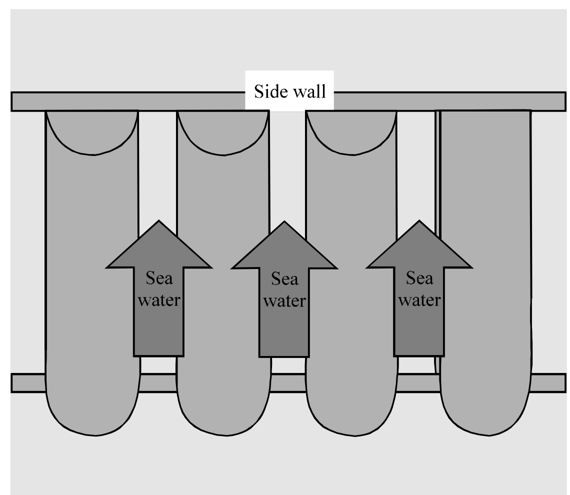

Fig. 2: Enlarged view of side well

Since, the change in capacity inside chambers C_h and C_l depends on the cross-sectional area of the chamber, they were represented in the following equation as A_h and A_l:

$$\frac{d\left(A_h H_h\right)}{dt}=Q_1-Q_2 \quad (7)$$

Furthermore, we could gain the following differential :

$$\frac{dH_h}{dt}=\frac{1}{A_h}\left(Q_1-Q_2\right) \quad (8)$$

$$\frac{dH_l}{dt}=\frac{1}{A_l}\left(Q_2-Q_l\right) \quad (9)$$

Equation 8 and 9 requests for the change in water level and flux in the two chambers in relation to time but the initial conditions are shown in Eq. 6 (Fig. 3):

$$H_h(0)=H_l(0)=\bar{H}_s \quad (10)$$

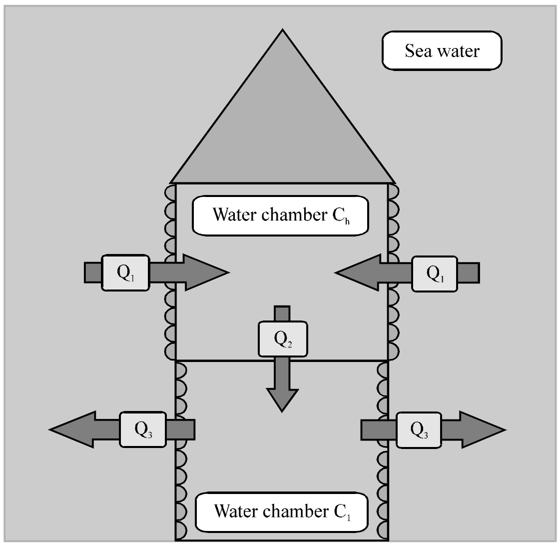

Fig. 3: Volume change of water

RESULTS AND DISCUSSION

Table 1 shows the device specifications used for calculations. The flux and change in water level at water depth H_s = 6 m, wave height H = 0.5 m and wave period T = 8 sec are shown in Fig. 4. Figure 4 shows the flux Q_2 that passes through the passage between the chambers keeps rising with a positive slope and has a fixed direction. This state is repeated through certain time periods. Also, if we look from outside the chamber on the peak of the wave at sea level, we can see that the water level in chamber C_h is almost identical to that in the sea level.

Also, the average flux Q_2 and the average change in water level Δh_{ave} between the two chambers and the

Table 1: Device specification used for numerical calculation

Device specification	Values
Area A_h of water chamber C_h (m^2)	6×5 = 30
Area A_l of water chamber C_l (m^2)	6×5 = 30
Width of the gap between the sea water and the chamber b (m)	0.7
Diameter of the connecting passageway between the chamber d (m)	1
Flux coefficient K_{1A}	0.971
Flux coefficient K_{1B}	0.500
Flux coefficient K_2	0.971
Flux coefficient K_{3A}	0.971
Flux coefficient K_{3B}	0.500

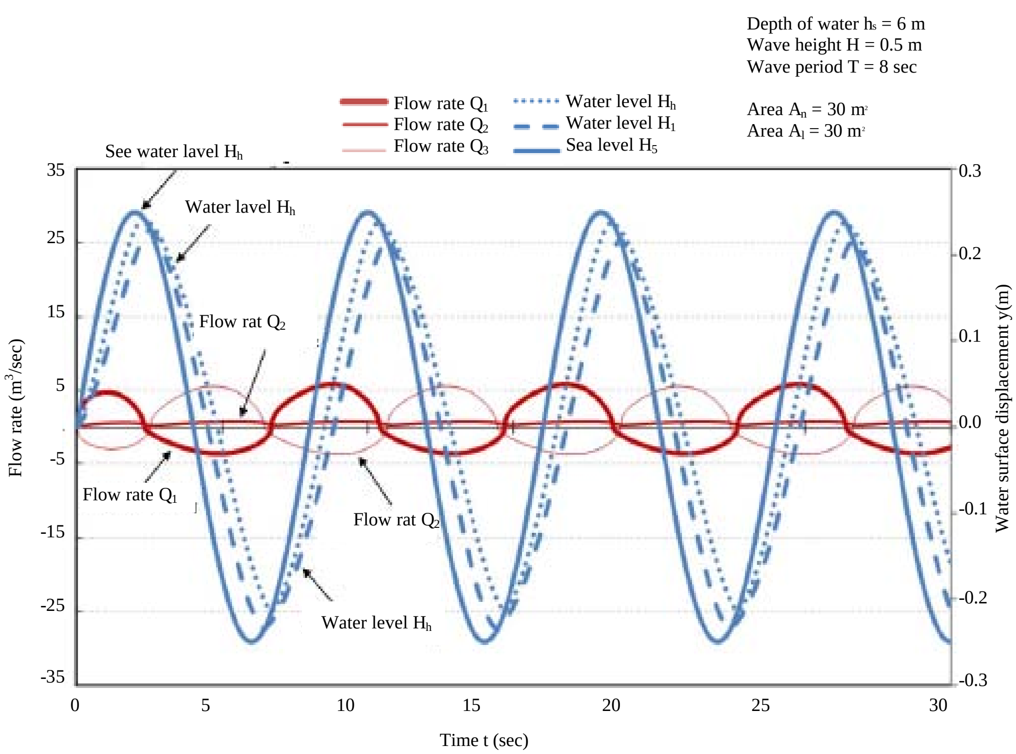

Fig. 4: Flux and water level displacement over time scale

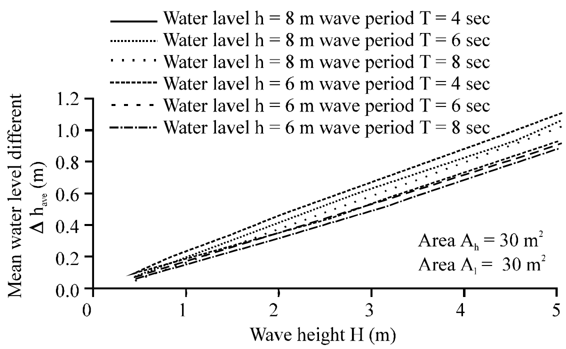

Fig. 5: Wave height and mean level difference by depth of water wave height, wave period

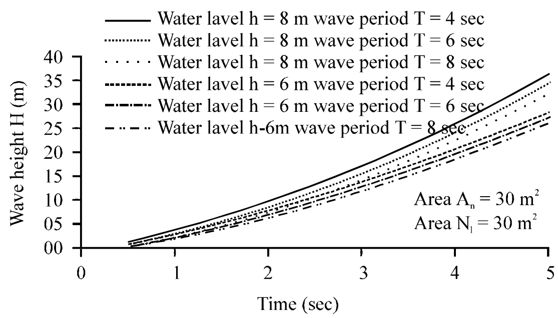

Fig. 6: Wave height and mean power by depth of water level, wave period

average power L_{oave} according to the hydraulic turbine have been calculated according to the wave height, period and water depth of the sine waves. The results are show at Fig. 4-6. As seen in Fig.4-6, the results are the highest when the wave height is large, the period short and the water depth large.

CONCLUSION

This research has analyzed the operation of the wave power generation system that uses the difference in water level between water chambers. The results of the research are as follows: the flux Q_2 that connects the chambers always increases in a positive rate. Here, we can see that it flows in a certain fixed direction and that this state is repeated in a certain time period.

If looked at from the peak of a wave in sea level outside the chamber, the water level in chamber C_h is almost identical to the sea level and if looked at from the trough, the water level in chamber C_l is almost identical to the sea level. The power has a high value when the wave height is large, the period short and depth large. This result is planned to be used as a reference data in future calculations in order to design the flux and change in water level inside the chamber without error.

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