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DEVELOPMENT OF WAVE POWER GENERATION DEVICE WITH RESONANCE CHANNELS

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ABSTRACT: The seawater exchange breakwater with L-shaped resonance channel was developed by Lee and Lee (2003). When the resonance period of the channel was fitted to the incident wave period, the water surface elevation in and flow rate through the channel were found to be maximum. In this study, we develop a wave power generation device with resonance channels. The device also works as a breakwater. The device has a sloping wall in which resonance channels are open to the sea. Behind the wall there is a reservoir which stores water passing through the channel and overtopping to the air. Under the water surface, the reservoir is connected to the rear side with a pipe in which wave power generation device exists. We conducted numerical experiments using the FLOW-3D in order to measure discharge of waves passing through the channel and overtopping to the reservoir. The results of numerical experiments showed that overtopping discharge becomes maximal around the analytically predicted resonance period.

Keywords: Wave power generation, resonance channel, numerical experiment

INTRODUCTION

Due to the depletion of fossil fuels, many inventors are looking for alternative energy sources. Our country is also trying to use the ocean energy by developing tidal, tidal current and offshore wind power generation devices at government level. The oscillating water column (OWC) which is one of the various wave energy technologies has high power generation efficiency. However, it cannot continually produce electric power. The OWC device generates electric power using the kinetic energy of air above the water surface inside enclosed space while this water is moved up and down by the incident waves. When the proper period of waves inside enclosed space is fitted to the incident wave period, it can increase power generation efficiency by resonance. However there are some limits to continue power generation because the motion of air is not always steady and it doesn't work when the storm attacks. Another type of power generation device is the overtopping wave energy convertor (OWEC). It can continually produce electric power but there is a limit to low head.

The Korea institute of ocean science and technology (KIOST) has been developing power generation devices of various types (i.e., floating-structure OWC, fixed-structure OWC, OWEC, etc) about 20 years since 1993. But wave power generation devices which were developed in our country are behind in comparison with developed countries in terms of efficiency and safety. Meanwhile, the seawater exchange breakwater with L-shaped resonance channel was developed by Lee and Lee (2003). When the resonance period of the channel is fitted to the incident wave period, the water surface elevation in and flow rate through the channel are found to be maximum.

In this study, we develop a wave power generation device with resonance channel. This device has advantage of using breakwater and wave power generation together. The device has a sloping wall in which resonance channels are open to the sea. Behind the wall there is a reservoir which stores water passing through the channel and overtopping to the air. Under the water surface, the reservoir is connected to the rear side with a pipe in which wave power generation device exists. Not only the device can maximize power generation efficiency but also can continually generate by inducing overtopping to the reservoir. Using the FLOW-3D we conducted numerical experiments on several cases (i.e., wave period, wave height, slope of a sloping wall and the height from the mean water level to the top of a sloping wall) in order to measure discharge of water passing through the channel and overtopping to the reservoir.

RESONANCE FREQUENCY OF CHANNEL WITH SLOPING WALL

As shown in Fig. 1, integration of the Euler equation from the entrance of the channel (i.e., point α) to the water surface in the channel (i.e., point β) gives the following equation

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$$-\frac{p_\alpha}{\rho}+g\left(\eta-z_\alpha\right)+\frac{1}{2}\left(v_\beta^2-v_\alpha^2\right)+\int_\alpha^\beta \frac{\partial v}{\partial t}ds=0 \tag{1}$$

The nonlinear terms of the kinetic energy are neglected in Eq. (1). The last term in the left side of Eq. (1) can be expressed as

$$\int_\alpha^\beta \frac{\partial v}{\partial t}ds \cong \frac{\partial v_\beta}{\partial t}\int_\alpha^\beta \frac{A_\beta}{A}ds \cong \frac{\partial^2\eta}{\partial t^2}\frac{1}{\sin\theta}\int_\alpha^\beta \frac{A_\beta}{A}ds \tag{2}$$

In order to derive Eq. (2) we apply $w_\beta = \partial\eta/\partial t = v_\beta \sin\theta$ and the continuity equation $Q = Av$. Therefore, Eq. (1) can be expressed as

$$p_\alpha = \rho g\left(\eta - z_\alpha\right)+\rho\frac{\partial^2\eta}{\partial t^2}\frac{1}{\sin\theta}\int_\alpha^\beta \frac{A_\beta}{A}ds \tag{3}$$

The surface elevation η and the pressure p_α can be expressed as

$$\eta = |\eta|\cos\left(\omega t+\varepsilon_\eta\right),\ p_\alpha = |p_\alpha|\cos\left(\omega t+\varepsilon_p\right) \tag{4}$$

Substituting Eq. (4) into Eq. (3) gives the following equation

$$|\eta|\cos\left(\omega t+\varepsilon_\eta\right)=\frac{z_\alpha+\dfrac{|p_\alpha|}{\rho g}\cos\left(\omega t+\varepsilon_p\right)}{1-\dfrac{\omega^2}{g}\dfrac{1}{\sin\theta}\displaystyle\int_\alpha^\beta \frac{A_\beta}{A}ds} \tag{5}$$

When the magnitude of the surface elevation becomes infinitely large at the given pressure, the resonance occurs. This means that the denominator of the right side of Eq. (5) must be zero. Thus, the resonance period is given by

$$T_r = 2\pi\sqrt{\frac{\displaystyle\int_\alpha^\beta \frac{A_\beta}{A}ds}{g\sin\theta}} \tag{6}$$

If the cross-section area of the channel is uniform and the distance from point α to the mean water level in the channel is l, we can get the following relation

$$\int_\alpha^\beta \frac{A_\beta}{A}ds = l \tag{7}$$

Substituting Eq. (7) into Eq. (6) gives the resonance period as

$$T_r = 2\pi\sqrt{\frac{l}{g}\frac{1}{\sin\theta}} \tag{8}$$

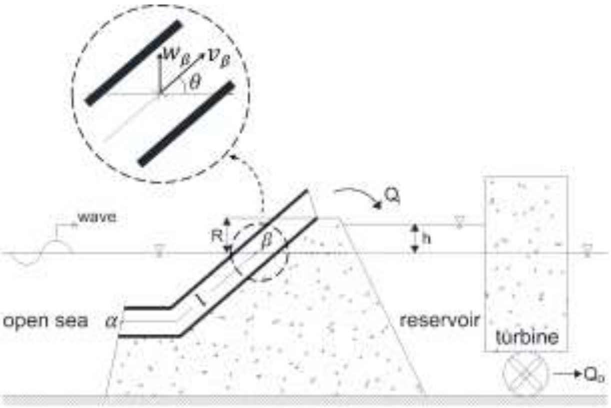

Fig. 1 Configuration of wave power generation device with resonance channel

MAXIMIZATION OF THE GENERATED WAVE POWER

In this study, we develop a wave power generation device with resonance channel, as shown Fig. 1. The incident wave passes through the channel and overtops to the reservoir, and then the water flows out of the reservoir through a pipe. The turbine in the pipe generates electric power by the water level difference h. When water passes through the channel, the water surface elevation in the channel will be maximum by inducing the resonance. After that discharge of overtopping to the reservoir will be also maximum. In Eq. (8), it is important to adjust the length l in the channel in order to get the resonance period T_r has the same value with the incident wave period T. The discharge of overtopping into the reservoir Q_i is

$$Q_i = \frac{V_i}{T} \tag{9}$$

where V_i is the water volume of overtopping into the reservoir by an incident wave. The discharge through the pipe Q_o can be expressed as

$$Q_o = a\sqrt{2gh} \tag{10}$$

where a is cross-section area of the pipe and h is the elevation of the reservoir water surface from the rear-side water surface. The generated wave power E is

$$E = \gamma Q_o h \tag{11}$$

where γ is the specific weight of water. If $Q_o h$ is maximum, the generated wave power will be maximum. To get the elevation of the reservoir water surface h, we derive the following equation using the previous continuity equation

$$A\frac{dh}{dt}=Q_i-a\sqrt{2gh} \tag{12}$$

where $A(h)$ is the surface area of the reservoir depending on the elevation of the reservoir water surface h. Using the finite difference method, Eq. (12) can be expressed as

$$h_{n+1}=h_n+\frac{\vartriangle t}{A_n}\left(Q_i-a\sqrt{2gh_n}\right) \tag{13}$$

where the subscript n denotes the number of each caculation step and $\vartriangle t$ denotes the time step size. Before the water overtops to the reservoir, $h=0$. When water enters the reservoir, the water elevation in the reservoir h and the discharge of outflow $Q_o\left(=a\sqrt{2gh}\right)$ increase. If the discharge of inflow and outflow are the same (i.e., $Q_i=a\sqrt{2gh}$), there is no more increase in the elevation of the reservoir water surface with the steady state. Water rising speed dh/dt is inversely proportional to the surface area of the reservoir A.

If the height from the mean water level to the top of a sloping wall R and the elevation of the reservoir water surface h with steady state are the same, 100% of the discharge of inflow Q_i can be used for the discharge of outflow Q_o for power generation purpose. The water volume of overtopping to the reservoir by an incident wave V_i is secured in the reservoir. This idea can be expressed by an equation as

$$R_{cr}=\frac{V_i}{\overline{A}} \tag{14}$$

where $\overline{A}$ is the averaged surface area from the mean water level to R. If $R\geq R_{cr}$, 100% of the discharge of inflow Q_i can be used for the discharge of outflow Q_o for the power generation. On the other hand, if $R<R_{cr}$, it has a loss of power generation due to water flowing backward into the channel. However, as R becomes higher, the discharge of inflow decreases more. Therefore, if $R=R_{cr}$, we can obtain the guaranteed discharge of the maximizing power generation. Thus, in this study, we need to find R of maximizing the generated wave power which is $Q_i\times R$ from Eq. (11).

NUMERICAL EXPERIMENTS

In this study, we measure the discharge of overtopping to the reservoir Q_i by changing the height from the mean water level to the top of the sloping wall R and then we compare with the generated wave power which is expressed as $Q_i\times R$. We conduct numerical experiments using FLOW-3D in order to measure the discharge of waves passing through the channel and overtopping into the reservoir.

We test 6 cases for different slopes (i.e., 30°, 45° and 90°) as shown Figs. 2 and 3. Figs. 2 and 3 show the cross section for experiments. We can exactly measure the stored water volume in the reservoir using uneven bottom of the reservoir. Water depth is $h=32cm$, water depth from the mean water level to the entrance of the channel is $h_i=11.5cm$ and the diameter of the channel is $d=7cm$. The incident wave height is fixed at $H=2.8cm$ with different incident wave periods such as $T=0.8,1.0,1.1,1.2,1.3,1.4,1.5,1.6,2.0\,\text{sec}$.

At first, we found periods with maximum water surface elevations on each case. Secondly, using these periods we measured the discharge of inflow Q_i for 4 cases as $R=0.5H,1.0H\ ,1.5H,2.0H$.

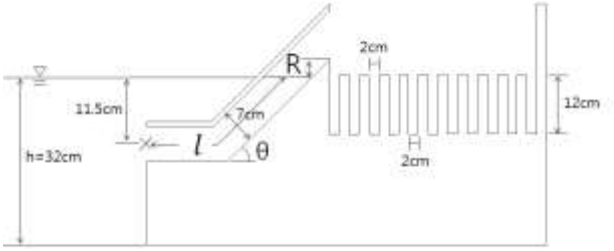

Fig. 2 Cross section with overtopping slope above the resonance channel

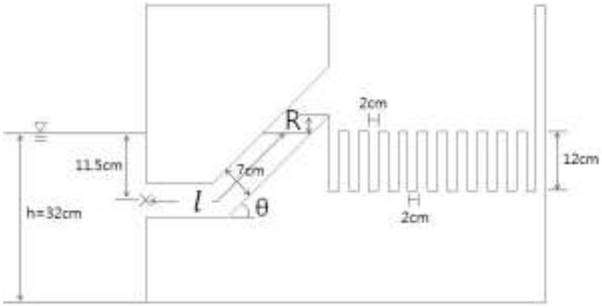

Fig. 3 Cross section without overtopping slope above the resonance channel

Table 1 Periods of maximum water surface elevation $T_{\max}$ and predicted resonance periods T_R on each case

Case		$T_{\max}$ (sec)	T_R (sec)	Relative error (%)
Fig. 2	30°	1.8	1.75	2.86
	45°	1.4	1.33	5.26
	90°	1.1	1.03	6.80
Fig. 3	30°	1.8	1.75	2.86
	45°	1.4	1.33	5.26
	90°	1.1	1.03	6.80

As shown in Table 1, the results of numerical experiments show that the water surface elevation in the channel becomes maximal around the analytically predicted resonance periods. Fig. 4 shows periods with maximum water surface elevations on each case. The maximum water surface elevation is the highest for the $30^{\circ}-$slope in both cases with and without overtopping slope above the resonance channel. As the water flow over the channel, the maximum water surface elevation of cases in Fig. 2 is lower than in Fig. 3.

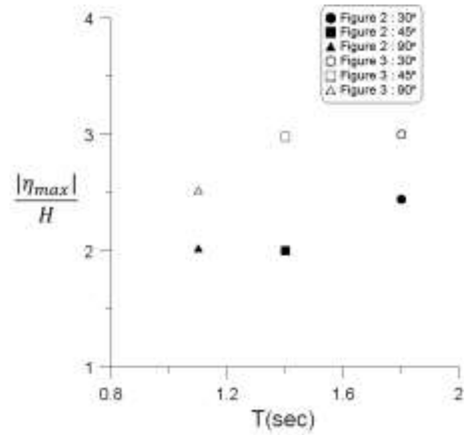

Fig. 4 Periods with maximum water surface elevation on each case

Fig. 5 shows the discharge of inflow per wave on each case. As shown in Fig. 5, R increases from $0.5H$ to $2.0H$, the discharge of inflow decreases. When the maximum water surface elevation of cases in Fig.2 is lower than cases in Fig. 3, the former discharge is also lower than the latter. When we calculate the average of the discharge $\overline{q_i}$, we divide accumulated discharge from 3rd or 4th wave to 12th wave by the number of waves as accumulated discharge due to the stability of the numerical experiment.

In Fig. 6, the value of y-axis is the averaged discharge multiplied by the height from the mean water level to the top a sloping wall R (i.e., $\overline{q_i} \cdot R$). Fig. 6 shows that the generated wave power is highest at $R = H$ except for the $90^{\circ}-$slope with overtopping slope above the resonance channel. The reason is that if R increases, the discharge of inflow decreases. Also, the generated wave power is highest for the $30^{\circ}-$slope without overtopping slope above the resonance channel for all cases.

In our next study, we will analyze more conditions to generate the maximum power such as cross-sectional area in the channel a_i, cross-sectional area in a pipe at the rear side a_o, surface area of the reservoir A and so on.

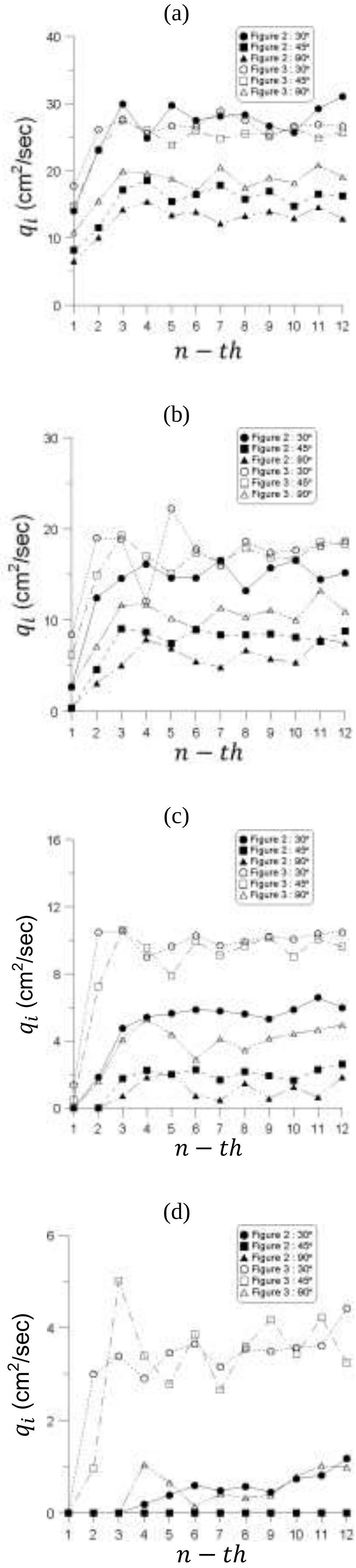

Fig. 5 Discharge of inflow per wave on each case:
(a) $R = 0.5H$, (b) $R = 1.0H$, (c) $R = 1.5H$, (d) $R = 2.0H$

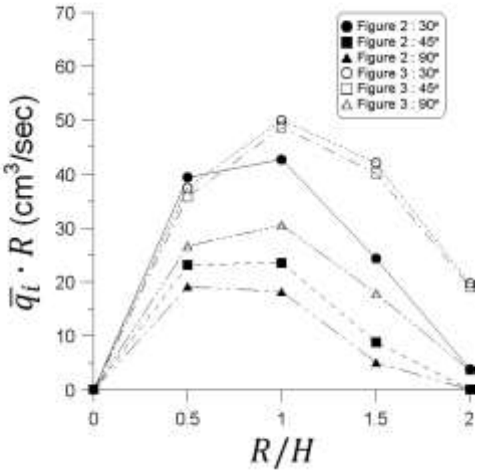

Fig. 6 Variation of $\overline{q_i} \bullet R$ on each R

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