Performance Prediction of OWC Type Small Size Wave Power Device with Impulse Turbine*

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Abstract

This paper investigates a small size wave power device with an impulse turbine installed in the breakwater near Niigata Port, Japan. The device consists of an air chamber, a turbine, a generator and pressure-relief valves. This study reveals the characteristics of each component in this system with impulse turbine and a direct current dynamo the power of which is consumed by a constant resistor. In this paper special features of the impulse turbine are found, and the system characteristics are briefly represented. The overall plant performance was analyzed using mathematical model of an oscillating water column (OWC) based on linear water wave theory and the special features of the impulse turbine.

Key words: OWC, Impulse Turbine, Wave Power Device, Fluid Machinery, Ocean Engineering

1. Introduction

The oscillating water column (OWC) wave power device is the most broadly studied type of wave power plant and one of the few to have reached the stage of full-scale prototype. The device essentially consists of a partially submerged chamber, open below the water surface, a turbine and an electric generator. The up-and-down motion of the internal free-surface (or OWC) produced by the incident waves makes the oscillating air flow through a turbine which drives an electric generator. There are a few full-scale prototypes installed at Sakata in Japan^{(1),(2)}, at Islay in Scotland⁽³⁾, at the Island of Pico in Portugal⁽⁴⁾, at Trivandrum in India⁽⁵⁾, and Mighty Whale of JAMSTEC in Japan⁽⁶⁾, and so on.

The present study investigates the performance of a pilot plant of wave power generation near Niigata Port which was developed in collaboration with Ministry of Land, Infrastructure, Transport and Tourism, Matsue National College of Technology, and Saga University in Japan. The pilot plant is installed on the breakwater 140m away from the coastline as shown in Fig.1~2. Figure 3 shows the configuration of the plant which is composed of an air chamber (or a caisson) of 2×2m size, a turbine-generator and four pressure-relief valves. The plant comprises an impulse turbine which has advantage for the complete self-starting, and it is particularly effective for the small size plants because the mechanical loss torque (or the friction loss torque) to the driving torque becomes relatively

larger than the large size plant. The impulse turbine⁽⁷⁾ is frequently used for OWC wave energy converters in the same way as the Wells turbine⁽³⁾, mainly because the turbines do not require any valves to rectify the alternating air flow, while having a fairly good maximum efficiency.

Fig. 1 Site of pilot plant installed on the breakwater near Niigata Port

Fig. 2 Wave power caisson installed on the breakwater.

Fig. 3 Configuration of wave power caisson

2. Characteristics of Turbine-Generator

2.1 Impulse Turbine

The specifications of the turbine are 0.458m diameter and 0.7 hub-to-tip ratio in Fig.4. Figure 5 shows the turbine configuration at the circular section of the mean radius, 0.389m. The turbine has 30 rotor blades and 26 guide vanes both upstream and downstream. Figs. 6~8 show the torque coefficient, the pressure drop coefficient and the efficiency which are the characteristics of the 0.65 scaled model. For the nondimensionalization of turbine, the tip speed, U , is often used as the representative velocity, while the special features of the

impulse turbine for wave power generation are found out by using the axial velocity, V_a , as representative velocity, such as the following equations:

$$\frac{1}{\phi} = \frac{U}{V_a}, \quad C_T = \frac{T_T}{\frac{1}{2} \rho_a V_a^2 A_T R_t}, \quad \psi = \frac{\Delta P}{\frac{1}{2} \rho_a V_a^2}, \quad \eta_T = \frac{C_T}{\psi} \quad (1)$$

where the nomenclatures are U/ϕ = tip-speed ratio, ϕ = flow coefficient, C_T = torque coefficient, T_T = torque, ρ_a = air density, annulus section area of $A_T = \pi(R_t^2 - R_h^2)$, R_t = radius of the rotor, R_h = radius of the hub, ψ = pressure drop coefficient, ΔP = pressure drop across the turbine, and η_T = efficiency.

Fig. 4 Configuration of impulse turbine

Fig. 5 Rotor and guide vane of impulse turbine

Figures 6~7 show the torque coefficient and the pressure drop coefficient which are found to be linear for the tip-speed ratio. In Fig.8 the efficiency of the experimental results also agrees with the values calculated by the linear lines of the torque and pressure drop coefficient. The maximum efficiency reaches 44.5% at the tip-speed ratio of 1.2. The torque and the pressure drop coefficients are approximated by the following equations:

$$C_T = -1.29 \frac{U}{V_a} + 5.98 \quad (2)$$

$$\psi = 6.38 \frac{U}{V_a} + 4.28 \quad (3)$$

and from Eqs. (1), (2) and (3) the torque and the pressure drop can be shown by:

$$T_T = C_T \left(\frac{1}{2} \rho_a V_a^2 A_T R_t \right) = \frac{1}{2} \rho_a A_T R_t (-1.29 U V_a + 5.98 V_a^2) \quad (4)$$

$$\Delta P = \psi \left(\frac{1}{2} \rho_a V_a^2 \right) = \frac{1}{2} \rho_a (6.38 U V_a + 4.28 V_a^2) \quad (5)$$

It is found that the torque and the pressure drop of the impulse turbine are expressed by the quadratic equation of the tip-speed and the axial velocity.

Fig. 6 Torque coefficient of impulse turbine against tip-speed ratio.

Fig. 7 Pressure drop coefficient across impulse turbine against tip-speed ratio.

Fig. 8 Efficiency of impulse turbine against tip-speed ratio.

2.2 Generator

The system installs a direct current dynamo of coreless type as a generator which is directly driven by an impulse turbine. The specifications of the generator are a rated power of 450W, a rated maximum power of 880W, a rated maximum rotational speed of 1500rpm, respectively. The typical characteristics of the DC dynamo with a constant load resistance are that the torque is proportional to the electric current, I , and the electromotive force, E , is proportional to rotational speed, N . The field test of the plant is operated by a load resistance of 22Ω to differ from the verified 5, 9.7, 20 and 35Ω . Therefore based on the above typical characteristics, the DC dynamo is analyzed from the results verified by the performance test. Figure 9 shows the open-circuit (or without load) voltage, E , that is the electromotive force, for the rotational speed. Figure 10 shows the inner resistance, r_0 , such as an armature resistance, calculated by the electromotive force, E , and the electric current, I , in relation to the several electric load resistances, R_L . Figure 11 shows the loss torque, T_{LOSS} , that is mechanical (constant term) and aerodynamic (quadratic term), which is the driving torque without the electric load. The loss torque is expressed by a quadratic equation. Figure 12 shows the torque generated by the dynamo, which is the driving torque minus the loss torque, for the electric current, I , with the several constant electric resistances. Consequently the following relationships are obtained:

$$E = C_{EN}N, \quad \frac{E}{I} = R_L + r_0, \quad T_{LOSS} = C_{T2}N^2 + C_{T0}, \quad T_G - T_{LOSS} = C_{TI}I \quad (6)$$

where the coefficients obtained from Figs.9~12 are $C_{EN} = 0.087\text{V/rpm}$, $R_L = 22\Omega$, $r_0 = 4.43\Omega$, $C_{T2} = 7.24 \times 10^{-8}\text{N-m/rpm}^2$, $C_{T0} = 0.295\text{N-m}$, $C_{TI} = 0.776\text{N-m/A}$.

The driving torque, the electric power and the efficiency of the generator is given by:

$$T_G = C_{TI} \frac{C_{EN} N}{R_L + r_0} + T_{LOSS} \quad (7)$$

$$P_{WG} = \frac{2\pi N}{60} (T_G - T_{LOSS}) \frac{R_L}{R_L + r_0} \quad (8)$$

$$\eta_G = \frac{T_G - T_{LOSS}}{T_G} \frac{R_L}{R_L + r_0} \quad (9)$$

Fig. 9 Electromotive force measured by open-circuit.

Fig. 10 Inner resistance, r_0 , estimated from electromotive force, E , and electric current, I , four electric load resistance, R_L .

Fig. 11 Loss torque of direct current dynamo.

Fig. 12 Torque generated by electric current of dynamo.

2.3 Turbine-Generator

The characteristics of the turbine-generator are obtained by coupling the above ones of both the turbine and the generator. Since the torque generated by the turbine, T_T , is equal to the driving torque of the generator, T_G , the following equation is obtained from Eqs. (4) and (7).

$$\frac{1}{2} \rho_a A_T R_t (C_{T1} U V_a + C_{T2} V_a^2) = T_G, \quad \because T_T = T_G \quad (10)$$

where the coefficients are $C_{T1} = -1.292$, $C_{T2} = 5.98$ from Eq. (2) and $U = (2\pi N/60)R_t$. The relationship between the axial velocity, V_a , and the tip speed, U , is obtained as follows:

$$V_a = \frac{-C_{T1}U + \sqrt{(C_{T1}U)^2 + 4C_{T2} \left(\frac{T_G}{\frac{1}{2} \rho_a A_T R_t} \right)}}{2C_{T2}} \quad (11)$$

where T_G is the function of only the tip-speed, U , from Eqs. (6) and (7). The output power of turbine is written by:

$$P_{WT} = T_G \frac{U}{R_t} \quad (12)$$

Figures 13~17 show the driving torque of the generator, the pressure drop across the turbine, the axial velocity of the turbine, and the output power for the rotational speed calculated by Eqs. (5), (7), (11) and (12). Figure 16 shows the output power of OWC (or the air chamber), the turbine, and the generator for the rotational speed, respectively. Figure 17 shows the efficiencies of the generator, the turbine, and the turbine-generator for the rotational speed.

Fig. 13 Driving torque of dynamo.

Fig. 14 Pressure drop across turbine.

Fig. 15 Axial velocity of turbine.

Fig. 16 Output power of oscillating water column, turbine and generator.

Fig. 17 Efficiency of generator, η_G , turbine, η_T , and turbine-generator, η_{TG} .

3. Coupling with Air Chamber and Turbine-Generator

The interaction between an air chamber and a turbine-generator is analyzed by coupling with the pressure and the flow rate ^{(9), (11)}. At the rated maximum rotational speed of 1,500rpm, the pressure drop across the turbine is about 2,000Pa as shown in Fig.14. The pressure ratio to the wave amplitude ($p/(\rho_w g H/2) \cong 1$) is found by preliminary calculations (as in Fig.19). Therefore the target wave height of a regular wave is selected to be about 0.4m because it is the maximum wave height to do sustainable operation without flow control valves (or pressure-relief valves).

The opening ratio (orifice area ratio), A_o/A_w , equivalent to an orifice is expressed by:

$$\Delta P = \frac{1}{2} \rho_a \left(0.61 \frac{A_o}{A_w} V_a \right)^2 \quad (13)$$

where ΔP is the pressure drop across the turbine and the contraction coefficient of the orifice is 0.61.

Figure 18 shows the equivalent opening ratio calculated from the pressure drop across the turbine with relation to the rotational speed. The target opening ratio becomes about 1/135 at 1,500rpm.

Fig. 18 Equivalent opening ratio, A_o/A_w .

4. Characteristics of Air Chamber (OWC)

The numerical methods for analyzing an OWC device are described under the condition that the linear water theory is applicable. In this paper the two dimensional characteristics of

the OWC device are solved by our previous method⁽⁸⁾. The method is based on the eigenfunction expansion method^{(9), (10)} and it was validated by a comparison with the experimental data of the fixed-type OWC and the floating-type OWC⁽⁷⁾. The configuration of the device in Fig.3 makes modeling simple such as Fig.19, and the characteristics of the device are calculated.

The target conditions are the opening ratio of the orifice, $1/135$, the water depth, $h=4.5\text{m}$, the chamber breadth, $B=2\text{m}$, the front wall submergence depth, $d=1\text{m}$, the incident regular wave height, $H=0.4\text{m}$. Figure 19 shows the space averaged elevation amplitude of water surface, z , the pressure amplitude inside the air chamber, p , the wave period, T , the efficiency of the OWC, η_{OWC} , and the reflected wave amplitude, a_r , based on the incident wave amplitude, a_i , against the wavelength, λ . The pressure ratio to the incident wave amplitude, $p/\rho_w g a_i$, becomes about 1 at the wave period of 7s ($\lambda/B \approx 22$) as in the previous assumption. The efficiency is 39% at the wave period of 7s. The reflection coefficient, a_r/a_i , is 0.8 at the wave period of 7s. Because the device size is small, therefore the wave dissipating effect becomes small for the target wave.

Fig. 19 Elevation of water surface in air chamber, z , pressure in air chamber, p , periodic of wave, T , reflected wave, a_r , efficiency of OWC, η_{OWC} , against wavelength λ .

5. Estimation of Total Characteristics of the Wave Power Generation System

The Total Characteristics that combined the air chamber and the turbine-generator are assessed. For the target regular wave ($H=0.4\text{m}$, $T=7\text{s}$), the efficiency of the air chamber, 39%, the efficiency of the turbine, 29.6%, the efficiency of the generator, 74.3% and, the total efficiency, 8.6% are obtained. The incident power of regular wave is 2.2kW with the air chamber width of 2m. Accordingly, the time average electric power becomes 189W. Since the wave power of irregular wave for the significant wave height ($H_{1/3}=0.4\text{m}$) is about 1/2 of regular wave, the time average electric power becomes 95W.

6. Conclusions

In this research, to carry out the performance prediction of the OWC type small size wave power device, the special features of the air chamber, the impulse turbine and the direct current dynamo were analyzed, and the following results were obtained.

- (1) The special features of the impulse turbine for wave power generation can be expressed by nondimensionalization based on the axial velocity, and it is found that the torque coefficient and the pressure drop coefficient are linear to the tip-speed ratio.
- (2) The driving torque and the electric power of the direct-current dynamo with the constant load resistance can be expressed by quadratic equation of rotational speed, and it is shown that the results agree with the measured data.
- (3) The characteristics of the turbine-generator are also expressed by quadratic formula, and it is found that the combination of the impulse turbine and the direct-current dynamo make the performance estimate easy.
- (4) As for the small size wave power device, the breadth of the air chamber cannot be taken long to the wavelength because of the small size. Consequently, the efficiency decreases as the chamber size becomes smaller. The estimated efficiency of the air chamber becomes 39% for the pilot plant.
- (5) The total efficiency of the pilot plant is estimated to be 8.6%, and the maximum average output, which can carry out sustainable operation safely for the restriction of the generator size, is estimated to be 190W for the regular wave, and 95W for the irregular wave.

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References

- (1) Goda, Y., Kanda, K., Ohneda, H., Odani, H., Suzuki, H., Hirano, M., and Takahashi, S., Construction of a Wave Power Extracting Caisson Breakwater for Field Experiment and Electric power Generation, 4th PACON, Tokyo, (1990), pp.419-426.
- (2) Suzuki, M., Arakawa, C. and Takahashi, S., Performance of Wave Power Generating System Installed in Breakwater at Sakata port in Japan, Proceedings of the 14th International Offshore and Polar Engineering Conference, ISOPE, Toulon, France, (2004), pp. 202-209.
- (3) Raghunathan, S., The Wells Air Turbine for Wave Energy Conversion, Prog. Aerospace Sci., Vol.31 (1995), pp.335-386.
- (4) Neumann, F., Brito-Mero, A., Didier, E. and Antonio Sarmiento, A., Pico OWC Recovery Project: Recent Activities and Performance Data, Proceedings of the 7th European Wave and Tidal Energy Conference, Porto, Portugal, (2007).
- (5) Thiruvengkatasamy, K. and Neelamani, S., On the Efficiency of Wave Energy Caisson in Array, Applied Ocean Research, Vol.19 (1997), pp.61-72.
- (6) Washio, Y., Osawa, H., Nagata, Y., Fujii, E., Furuyama, H. and Fujita, T., The Offshore Floating Type Wave Power Device "Mighty Whale": Open Sea Tests, Proceedings of the 10th International Offshore and Polar Engineering Conference, ISOPE, Seattle, USA, (2000), pp.373-380.
- (7) Setoguchi, T., Takao, M., Santhakumar, S., and Kaneko, K., Study of an Impulse Turbine for Wave Power Conversion: Effects of Reynolds Number and Hub-to-Tip Ratio on Performance, Journal of Offshore Mechanics and Arctic Engineering, ASME, Vol.126, No.2 (2004), pp.137-140.
- (8) Suzuki, M. and Arakawa, C., Numerical Methods to Predict Characteristics of Oscillating Water Column for Terminator-Type Wave Energy Converter, International Journal of Offshore and Polar Engineering, ISOPE, Vol.15, No.4 (2005), pp.292-299.
- (9) Takai, T., Yamamoto, S., Isshiki, H., and Nekado, Y., Diffraction and Radiation of Wave Due to Two Vertical Flat Plates (in Japanese), Journal of kansai Society of Naval Architects, The Kansai Society of Naval Architects, Japan, No.164 (1977), pp.43-49.

- (10) Ijima, T., Tabuchi, Y. and Yumura, Y., On the Free Motions of a Floating Rectangular Body in Waves of Finite Water Depth (in Japanese), Technology reports of Kyushu University, Vol.45, No.1 (1972), pp.35-43.
- (11) Suzuki, M. and Arakawa, C., Design Method of Wave Power Generating System with Wells Turbine, International Journal of Offshore and Polar Engineering, ISOPE, Vol.14, No.3 (2004), pp.227-232.