CHAPTER 262

Wave Power Conversion by a Prototype Wave Power Extracting Caisson in Sakata Port

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1. INTRODUCTION

Ocean wave energy is clean and inexhaustible. Repeated oil crises and the urgent need for environmental preservation on a global scale have made utilization of ocean wave energy increasingly important.

The Japanese Ministry of Transport has been developing a wave power extracting caisson breakwater which can absorb wave power and convert it into electric power. The breakwater shown in Fig.1 is a composite breakwater with a special caisson for absorption and conversion of wave power. The caisson has a so-called air chamber where wave power is converted into air power. The air power activates a turbine-generator in the machine room on the caisson. The use of the breakwater as a wave power converter will effectively cut down the power generation cost. This breakwater also aims at the improvement of the wave resisting stability and performance as a breakwater by absorbing the wave energy.

The research and development work on the wave power converter is being carried out through collaboration by the First District Port Construction Bureau, the Port and Harbour Research Institute and the Coastal Development Institute of Technology under the

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Figure 1 Wave Power Extracting Caisson Breakwater in Sakata Port

Photo 1 Wave Action on Wave Power Extracting Caisson

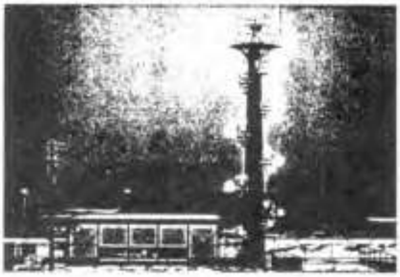

Photo 2 On-land Observation House and Illuminated Tower

guidance of the home office of the Ministry of Transport. The Port and Harbour Research Institute had conducted basic research for five years since 1982[1)2)3)4)]. The 1st District Port Construction Bureau, Ministry of Transport, began a field verification experiment for the breakwater from 1987 in the form of a joint study with the Coastal Development Institute of Technology and twenty private companies. A test breakwater was constructed in the summer of 1989 at Sakata Port in Yamagata Prefecture[5)6)7)]. The breakwater began the power generation in the winter of 1989. Photo 1 shows the wave action on the completed caisson and Photo 2 shows the on-land observation house and a tower illuminated by the converted energy.

The field experiments were conducted for the five years from fiscal 1987 through fiscal 1991 aiming at the following items:

1) to confirm the design method of the breakwater caisson including the air chamber against wave forces,
2) to verify the design method of the air chamber, turbine and generator as a wave energy converter,
3) to study methods of constructing the breakwater
4) and also to demonstrate utilization of the power output for various uses.

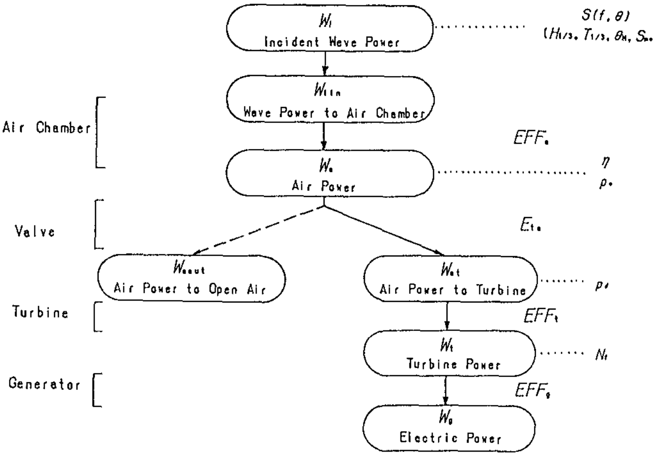

Figure 2 Energy Conversion Process

This paper introduces the system with a wave power extracting caisson in the field experiment and the results of the field experiment, especially on the wave power conversion.

2. POWER CONVERSION BY THE CAISSON AND TURBINE GENERATOR

Figure 2 shows the power conversion process by the wave power extracting caisson and its turbine generator. The wave power is converted first into air power in the air chamber, then into turbine power by the turbine and finally into electric power by the generator as follows:

1) W_i denotes the incident wave power which can be obtained from the wave spectrum. The incident wave power is the energy rate which the incident wave transports in an unit time and length. W_{iin} represents the wave power going into one caisson.
2) W_a denotes the air power converted from wave power in the air chamber, which can be estimated by the vertical speed of water surface movement and the air pressure in the air chamber and the horizontal area of the air chamber. The conversion efficiency EFF_a from wave power to air power is given by W_a/W_{iin}. The efficiency depends on the ratio of the air chamber width B to the wavelength $L_{1/3}$, and the turbine diameter R_t (actually the total area of turbine opening and valve openings, etc.). The conversion efficiency also varies with submerged depth d_c of the curtain wall of the front wall of the air chamber and the height D_0 of the air chamber1)2). For example, the air chamber width is 13% the wavelength of a wave of 7 s to obtain a high conversion efficiency with a small width as much as possible..
3) W_{aout} represents the wave power released to the atmosphere from control valves and dummy nozzles, while W_{at} represents the air power into the turbine. The sum of W_{aout} and W_{at} equals to the

air power W_a. The ratio W_{at}/W_a is defined here as the utilization rate E_{ta} of air power. The utilization rate of the air power in the system of the experiment is always less than 0.5 because of the existence of the dummy nozzles as will be described in Chapter 3.

4) W_t represents the turbine power which can be obtained from the turbine torque and the rotation speed. The conversion efficiency EFF_t is given as the ratio W_t/W_{at}. The fundamental characteristics of the turbine including the turbine efficiency can be obtained from steady wind tests. The turbine efficiency varies with the attacking angle of wind to the turbine blade, and therefore the turbine speed should be controlled to bring a high conversion efficiency [2].

5) W_g denotes the electric power which can bc evaluated by the electric voltage and current. The electric current is determined by the connected electric loads and therefore the electric load should be controlled considering the turbine power . The electric load is controlled using the signal of the speed of turbine in the experiment. The turbine efficiency EFF_g is given by the ratio W_t/W_g, which is usually given from a factory test.

   The speed of the turbine fluctuates with the frequency of the waves and also that of the wave group. The strength of the fluctuation depends on the inertia moment I_{tg} of the turbine generator.

6) The conversion efficiency EFF_{atg} from wave to electric power is indicated as the product of EFF_a, EFF_t and EFF_g. However by the influence of the control valves and dummy nozzles, the actual conversion efficiency EFF_{atgo} decreases to $EFF_{atg} \times Eta$.

3. WAVE POWER EXTRACTING CAISSON IN THE EXPERIMENT

3.1 Design of Wave Power Conversion System

A caisson of the Second North breakwater of Sakata Port is used for verification experiments, as shown in Fig. 3. The breakwater is

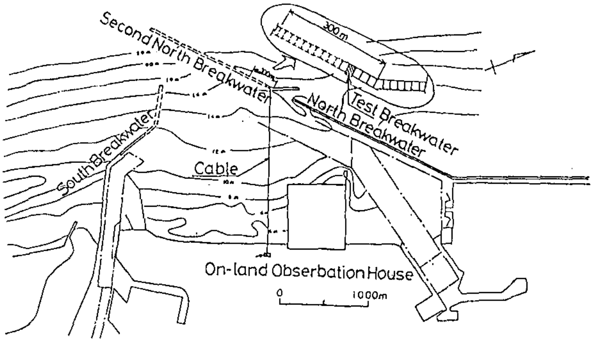

Figure 3 Location Map of Sakata Port

now under construction as a composite breakwater, with a planned length of 1,900 m. The depth of the water is 18 m at the construction site. The sea bottom foundation is mostly sandy with viscous soil in some places. A settlement of the caisson of about 1 m is predicted.

In designing a wave energy converting system, it is necessary to know the wave power available in the designed places and to determine the use of the converted energy. Then the frame plan of the system can be established. The fundamental dimensions of the components of the system such as the diameter of the turbine are determined based on the frame plan. Finally, the components are designed in detail.

Wave data at Sakata Port for about twenty years were analyzed to find the wave conditions there4). The system was designed to operate for the waves of 1 to 5 m, and the wave with $H_{1/3}$ = 2.2 m and $T_{1/3}$ = 7 s was selected as a main wave to discuss the conversion efficiencies. However, the design wave for the stability of the air chamber and other devices is $H_{1/3}$ = 10.2 m and $T_{1/3}$ = 14.5 s. Numerical calculations based on the thermodynamics and wave-kinematics theory[123] were conducted to determine the fundamental dimensions of the components of the system.

The wave power extracting caisson has an air chamber of 7 m wide as shown in Fig. 4. The caisson is 20 m long in the direction of the breakwater alignment line. The height is +12.5 m above the datum level level. The horizontal area is 115 m^2, not including the thickness of the walls.

Figure 5 shows a concept of the machine room. The air flow converts its energy into the kinetic energy by rotating the turbines and the generator shown in Fig. 6, installed at the center of the machine room in the upper portion of the caisson. Two Wells turbines 1,337 m in diameter are employed to get a one-way rotation from the reciprocal flow of the air and sandwich the generator to make a tandem type arrangement canceling the forces

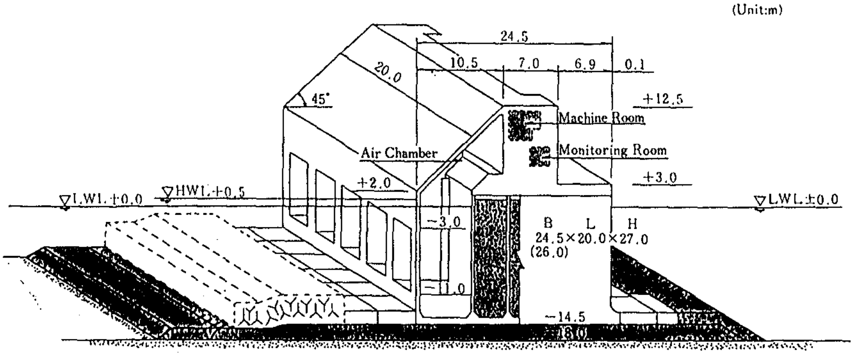

Figure 4 Shape of the Caisson Breakwater

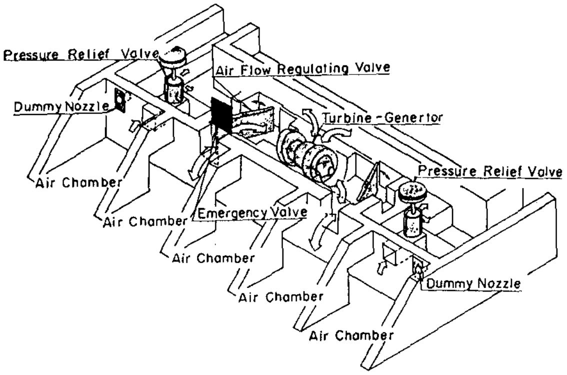

Figure 5 Conceptual View of the Machine Room

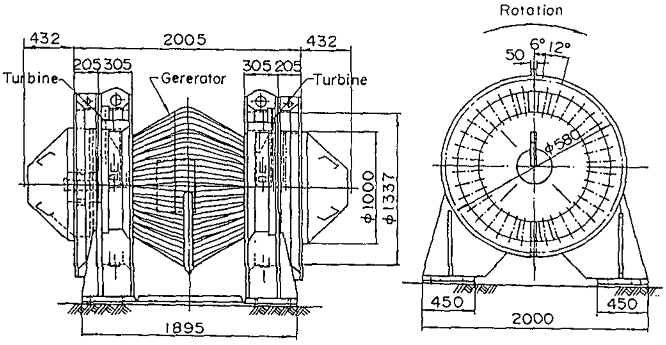

Figure 6 Turbine and Generator

that work in the axial direction of the turbines. The generator is a 200 V synchronous generator with a rated output of 60 kW and a maximum revolution of 3,000 rpm.

The protection devices that control the air flow from the air chamber to the turbine consist of three types of valves: the air-flow regulating valve (bypass valve), the pressure release valve and the emergency cutoff valve. Figure 7 shows the air-flow regulating valve. The valve is of a rectangular box with a butterfly valve inside. The air flow can be controlled by the rotation of the butterfly valve. An electric actuator is equipped to rotate the butterfly valve according to the signal of the turbine speed. The valve closes the opening by 1/4 of the full rotation angle when the turbine speed exceeds a certain limit (simultaneously the valve opens the other opening to release the extra air power. If the turbine speed exceeds again the limit, the valve closes the opening again by one more 1/4 of the full angel. When the turbine speed becomes lower than a certain value the valve opens the opening by every 1/4. Power generation is stopped when waves are extremely large (when the significant wave height is above 5 m) by terminating the air flow to the turbine and simultaneously fully opening the air flow regulating valve.

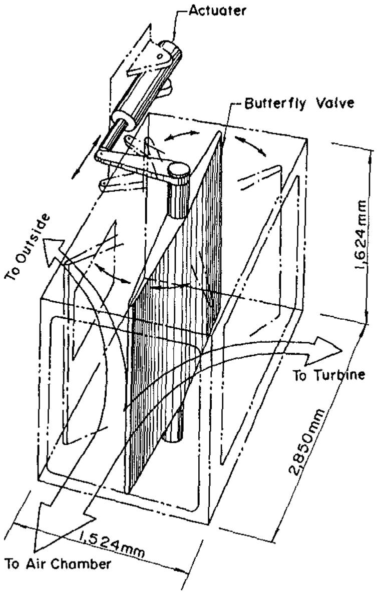

Figure 7 Air-flow Regulating Valve

It should be noted that the diameter of the turbine in the experiments is set to be much smaller than that of the optimum turbine predicted by the amount of air power from the air chamber. This is because of the limitation of research funds. Two dummy nozzles are installed to release the extra air power, which corresponds to almost half of the total air power.

The power generated is transmitted to the on-land observation station through an underwater cable, where it is consumed by electric resistors. Experiments are also being made to utilize the electric power for various appliances to prepare for the application of the system for actual use.

3.2 Operation of the system

The power conversion of the system can be adjusted by changing the setting of the electric load against turbine speed, the threshold pressure of the pressure release valves, and the threshold turbine speed to open/close the air-flow regulating valves.

The system started the power generation from December 1st, 1989. In fiscal 1989, the system was operated rather discreetly under Setting I, while in fiscal 1990, experiments were conducted under Setting III for the optimized control method to generate larger amount of electric power. In the setting III, the electric load is proportional to the 3rd power of the turbine speed and the electric power is 60 kW when the turbine speed is 1800 rpm. The threshold pressures of the two pressure release valves are 1.34 and 1.61 tf/m^2, and the air flow regulating valve is controlled to open one step (1/4) at 2000 rpm and to close one step (1/4) at 1700 rpm in the setting III. The results of power conversion with the setting III is described in this report.

Table 1 summarizes the dimensions of the conversion system in the experiment, where A_t, A_p, and A_n denote the opening area of the turbine, the dummy nozzle, the pressure release valve,

Table 1 Experimental system and Full-size System

	Experiment system	Full-size system
Air Chamber	$B=6.75m$, $l_B=20m$ $D_O=8m$, $d_c=3m$, $A_w=115m^2$	$B=6.75m$, $l_B=20m$ $D_O=8m$, $d_c=3m$, $A_w=115m^2$
Turbine	$2R_t=1.337m$ $A_t=0.6185m^2 \times 2$ $I_{tg}=55.0kgm^2 \times 2$	$2R_t=2.40m$ $A_t=1.99m^2 \times 2$ $I_{tg}=1650.0kgm^2 \times 2$
Generator	60kW (1800rpm-60kW)	200kW (1000rpm-200kW)
Air-Flow Regulating Valve	close – Open (1700rpm) (2000rpm) $c_{dv}\varepsilon_v=0.00892$ (=1/112)	close – Open (1000rpm) (1300rpm) $c_{dv}\varepsilon_v=0.00892$ (=1/112)
Dummy Nozzle	$A_n=0.0746m^2 \times 2$ $c_{dv}\varepsilon_n=0.00130$ (=1/770)	No Dummy Nozzle
Pressure Release Valve	$A_p=0.481m^2 \times 2$ $c_{dv}\varepsilon_p=0.00671$ (=1/149) $p_{prv}=1.30$, $1.61tf/m^2$	No Pressure Release Valve

respectively, C_{dv} is contraction coefficient, ε is opening ratio of each opening, P_{prv} is threshold pressure of the pressure release valve. In the table, the dimensions of the full-size system is also listed which will be discussed later.

3.3 Measurement

A number of sensors are incorporated in the caisson and the power generating system to make measurements in the following four categories.

(1)· Wave conditions (directional spectrum, heights, periods and directions of incident waves)
(2) Stability of the breakwater (wave pressure and air pressure)
(3) Stability of the wall members (stress of the reinforcement)
(4) Air output and power output (water level and pressure in the air chamber, turbine speed, power output)

Data are amplified and converted into optical signals before they are sent by an opto-electric power combination cable to the observation station on land, where they are analyzed and processed using four personal computers. In addition to the above procedure, detailed data are sampled and stored in a digital recorder, for 20 minutes at one operation, for further analysis of the breakwater stability . However, only the data concerning with the incident waves and the power conversion are discussed in this report.

4. OBSERVED WAVES

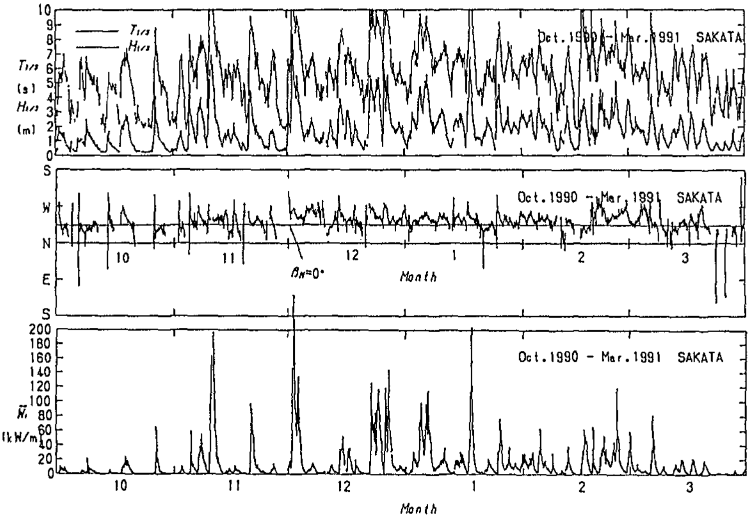

Figure 8 Variation of Significant Wave and Wave Power

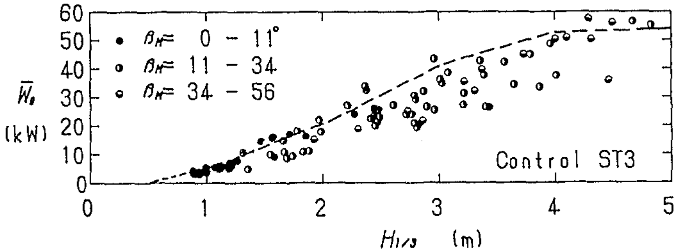

Figure 9 Incident Wave Power

Figure 8 shows the wave data from October 1990 to March 1991. The significant wave height and period, mean wave direction and wave power are shown in the figure. The average significant wave height and period were 1.72 m and 6.2 s, and the average wave power was 13.9 kW/m during this period. The wave height varies very widely and exceeds 5 m several times. The largest value of the significant wave height reached 8.67 m on December 2, 1991. The mean wave direction was usually northwest, which is almost perpendicular to the breakwater alignment. The wave power varies significantly and exceeds even 100 kW/m.

Figure 9 shows the measured and calculated incident wave power. The calculated power is obtained from a standard wave spectrum which was used in the design of the system. For example the calculated incident wave power becomes 18 kW/m at $H_{1/3}$ = 2.2 m and is 67 kW/m at $H_{1/3}$ = 4 m when the mean incident wave angle is 0 degree. The measured values agree well with the calculated ones.

The wave power can be estimated easily by the following formula with significant wave height $H_{1/3}$ and period $T_{1/3}$.

$$W_t = \kappa H_{1/3}^2 T_{1/3} \quad (\mathrm{kW/m}) \tag{1}$$

where, κ_w is 0.4 - 0.5 (kW/m^3/s) in Sakata. Which is almost equal to the expected value in the preliminary studies[4]. It was also found that the wave power in sakata was reduced to 85 % of that for long crested waves due to directional spreading.

5. WAVE POWER CONVERSION

Figure 10 gives an example of the records of power generation, i.e., the water surface elevation and the air pressure in the air chamber, opening of the air flow regulating valve, pressure difference in the turbine and turbine speed, and power output for 20

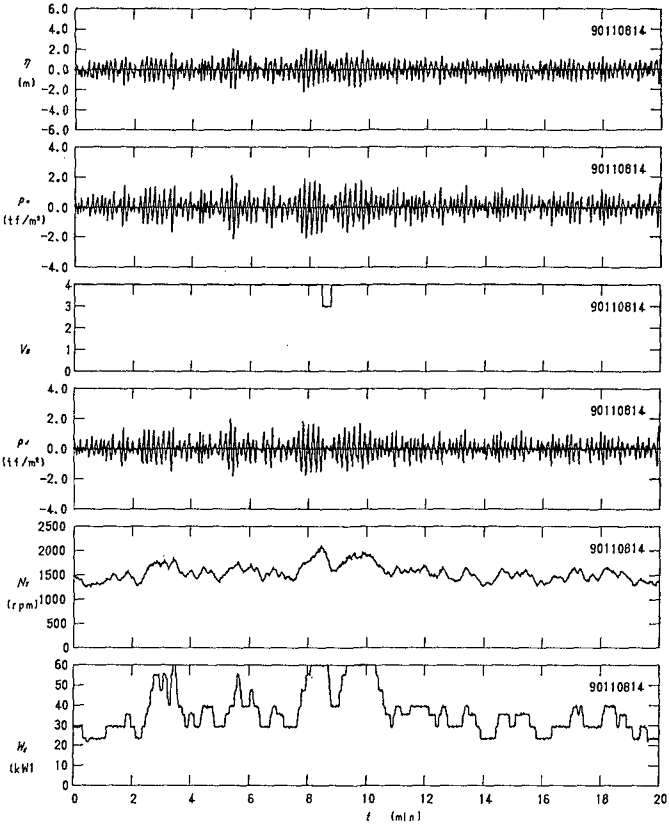

Figure 10 Analogue Data of Wave Power Conversion

minutes, that were recorded at 14:00 on November 8 in 1990, when the significant wave height and period were 3.01 m and 7.9 s, respectively, and the incident wave power was 539 kW/20m. The turbine rotation varies from 1250rpm to 2100 rpm and the electric power varies from 20 kW to 60 kW. As the turbine speed exceeds 2000 rpm the air flow regulating valve opens to reduce the air flow to the turbine as shown in the figure. The average electric power is 36.4 kW, and the conversion efficiencies from wave power to air power, from air power to turbine power and turbine power to electric power are 0.59, 0.37 and 0.91, respectively. However, a large amount of air power is released by the dummy nozzles and valves. Therefore, the utilization rate of air power is very low (0.34). If all the power is used, the electric power is about 100 kW.

Table 2 shows the monthly averaged values on power conversion from October 1990 to March 1991. For example, the average incident wave power is 20.3 kW/m and average electric power is 13.25 kW/m in January 1991. The time when the electric power is small and less than 1 kW, occupies only 13 % in the month, while the time occupies 51 % in October 1990.

Figure 11 shows the variation of the electric power to the significant wave height. The electric power increases according to the increase of the wave height. However, the electric power becomes almost constant at about 55 kW where the wave height is above 4 m.

Table 2 Power Generation in Each Month

Year/Month	'90/10	'90/11	'90/12	'91/1	'91/2	'91/3
$(W_i)_{ave}$ (kW/m)	3.3	13.0	23.9	20.3	15.0	6.7
$(W_g)_{ave}$ (kW)	6.03	10.65	13.34	13.25	10.88	9.73
Operation Time	168	172	156	154	155	193
Ratio($W_g = 0$ kW)	0.39	0.25	0.13	0.02	0.13	0.18
Ratio($0 \leq W_g < 1$)	0.51	0.28	0.24	0.13	0.23	0.23

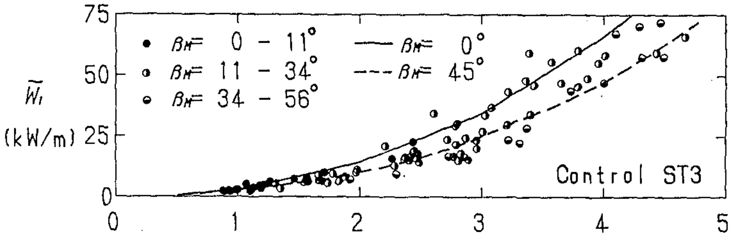

Figure 11 Electric Power

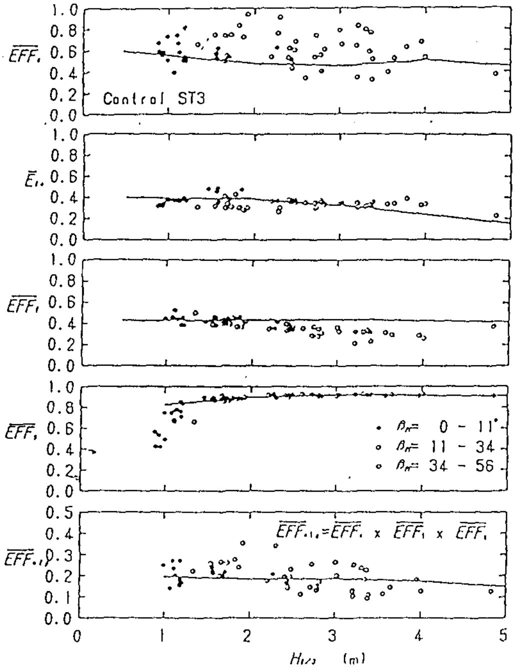

Figure 12 Conversion Efficiencies

This is due to the automatic control of the valves. The system can generate electric power from $H_{1/3}$ = 1 m to 5 m as designed. The calculated values for the normal incident waves are shown in the figure by a dotted line. The calculated values, which were used in the design of the present system, agree with the experimental ones for small wave angle. The calculation was based on the thermodynamics and wave-kinematic theory1)2)3).

The conversion efficiencies in thc experiment are shown in Fig.12. The conversion efficiency from wave to air power is from 0.4 to 0.8. The turbine efficiency is from 0.2 to 0.5. The generator efficiency is about 0.5 when the wave height is large. The total efficiency which is given by the product of EFFa, EFFt and EFFg is from 0.1 to 0.3 approximately. However this system includes the control valves and dummy nozzles so that the actual efficiency should be multiplied by the air power utilization rate.

The solid lines indicate the prediction by the thermodynamics and wave-kinematic method. The experimental values of the air power conversion efficiency are larger than the predicted values. This is because only one wave power extracting caisson is installed between the reflective caissons and therefore reflected and refracted waves from neighboring caisson can increase the incident wave power into the caisson with wave power conversion.

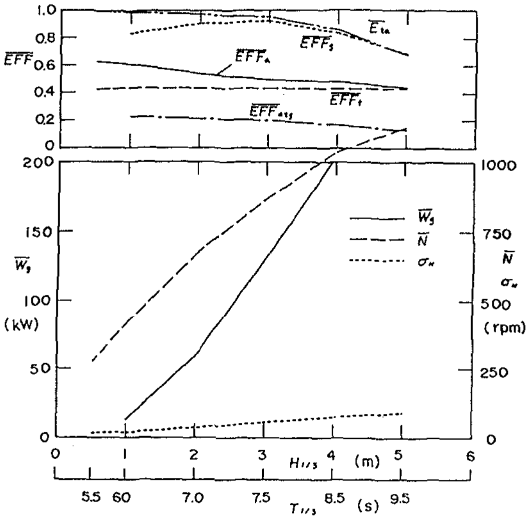

Figure 13 Power Generation by a Full-size System

Table 3 Prediction of Power Generation

	Unit	Sakata (one year)	Sakata (winter)	Wadomari (one year)	Kashima (one year)
Ave. Significant Wave Height	m	1.19	1.79	1.18	1.50
Ave. Significant Wave Period	s	5.64	6.40	7.13	7.88
Ave. Wave Power	kW/m	10.56	19.42	7.60	13.95
Time Rate of Power Generation	%	40.2	65.0	50.0	67.0
Ave. Electric Power	kW/20m	27.3	49.3	23.0	40.9

6. WAVE POWER CONVERSION BY A FULL-SIZE SYSTEM

The turbine-generator is small in the experiment. A full-size system with a larger turbine generator can produce the electricity more. Figure 13 shows the calculated result of the wave power conversion by a full-size system with an optimal turbine generator for the conditions in Sakata Port. The diameter of the turbine is 2.4 m, which is almost twice that in the experiment. The rated power of the generator is 200 kW. The turbine speed is expected to be 700 rpm and the electric power is 75 kW when the significant wave height is 2.2 m. The electric power becomes 200 kW when the significant wave height is 4 m.

Table 3 shows the predicted wave power conversion by a full-size system in Sakata Port, using the conversion efficiencies in Fig. 13 and the observed wave data from 1990 -1991. In the table the predicted results for Wadomari Port in Okino-erabu Island and

Kashima Port in addition to Sakata Port during only winter time are shown for comparison. The annual average electric power in Sakata Port is 27.3 kW and the average value within winter time is 49.3 kW. In Kashima Port the wave power conversion can be made for 67 % of time and the annual average electric power is 40.9 kW.

7. CONCLUDING REMARKS

The field experiment was conducted very successfully, although several severe storms attacked the caisson. The characteristics of the wave-activated power generation by the wave power extracting caisson were revealed and the design method of the system was confirmed in this prototype experiments.

Several tests to utilize the output electricity were also made in the experiments. It is important not only to improve the power converter but also to develop the energy utilization systems. The second stage of the field experiment was already started from April 1992, where several utilization systems including a large-scale water pumping system are to be tested and some improvements of the caisson with the turbine generator will be tested.

The field experiments were carried out under the guidance of the advisory committee chaired by professor Y. Goda. The experiments was conducted by the collaboration with many people. The authors wish to express their sincere gratitude to all the people. The authors also wish to thank Dr. Takayama for his crucial review of the manuscript.

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