CHAPTER ONE HUNDRED NINETY TWO

WAVE POWER EXTRACTION AT COASTAL STRUCTURE BY MEANS OF MOVING BODY IN THE CHAMBER

Hideo KONDO[1], M.ASCE, Tomiji WATABE[2] and Kenji YANO[3]

Abstract

A series of study on wave power extractors which may utilize a part of the coastal structures has been performed by the group of faculties of Muroran Institute of Technology since 1978. Three kinds of extractor belonging to the so-called fixed type had been developed and studied in the laboratory. They are the air chamber with flap, the wave turbine system and the pendulor system. The last two systems have been subsequently studied at the field test plant constructed at Port Muroran. The study shows that the pendulor system brings an excellent power conversion efficiency.

1 INTRODUCTION

Numerous apparatus have been proposed for the purpose of extracting usable energy from sea waves. However, none of them except the Masuda air buoy as navigational markers are in practice because of the economical difficulty to cope with oil. These extractors are classified roughly into two types, namely, the floating and the fixed ones. Table 1 presents a further classification of the two types of extractors from the viewpoint of dynamic property and direction of body or water, etc.

Much effort had been devoted to develop the floating type extractors just after the 1973 oil crisis. Generally speaking, they require large floating bodies with durable mooring equipments, which raises the cost of energy to be produced. The idea of so-called fixed coastal type has a longer history than the floating one but less attention had been payed for it in the 70's. The drawback of the floating type made a few groups reexamine the merit of fixed type.

Coastal deffensive structures, namely, breakwaters, dykes, and revetments have been so designed as to reflect and/or to dissipate the incoming waves. If we could extract a considerable amount of the incident wave energy at these structures without spoiling their essential functions, the cost of energy must be remarkably decreased from that by the conventional apparatus. With this line of thought, the group of civil, mechanical and electric engi-

1 Professor of Civil Engineering, Muroran Institute of Technology, 27-1 Mizumoto-Cho, Muroran, 050 JAPAN
2 Professor of Mechanical Engineering, ditto
3 Research Assistant of Civil Engineering, ditto

Table 1 Classification of Wave Power Extractors
[Notations in the parenthesis after the name of extractors are as follows. Fin;Finland, US;United States of America, UK;United Kingdom, J;Japan, NY; Norway, RSA;Republic of South Africa]

	DYNAMIC PROPERTY	DIRECTION OF BODY MOTION OR WATER, ETC.		NAME OF EXTRACTOR(COUNTRY)
FLOATING TYPE	PASSIVE SYSTEM (ISLAND SYSTEM)	Wave Pressur		Törnkvist(Fin)
		Wave Run-up		Dam Atoll(US)
	RESONANT SYSTEM	Wave Pressure		Flexible Bag(UK), CLAM(UK)
		Heaving	Buoy	Masuda Air Buoy(J), Belfast(UK)
				Point Absorber(NY), Tail Tube(UK)
			Attenuator	Kaimei(J)
			Terminator	OWC(UK), Plunger Shaped(UK)
		Rotating	Rolling	Salter Duck(UK)
			Pitching	Cockrell Raft(UK)
		Underwater		Oscillating Cylinder(UK)
FIXED TYPE	PASSIVE SYSTEM (PROGRESSIVE WAVE)	Wave Pressure	Vertical	Bottom Pressure(US)
			Horizontal	Pressure Diaphragm(J)
		Inflow		HRS Rectifier(UK)
		Overtopping		Wave-Current(J)
	RESONANT SYSTEM (SATNDING WAVE)	Vertical		NEL-OWC(UK), SWEC(RSA)
				Air Chamber with Flap(J)
		Horizontal		Wave Turbine(J)
				Pendulor(J)

neering faculties of the institute headed by the senior author had tried to find the fixed type extractors which can be set within coastal structures and be easily operated , since 1978. The three extractors developed are the resonant fixed type ones and are those underlined in Table 1.

2 AIR CHAMBER WITH FLAP

The first extractor studied consists of an air chamber with the oscillating flap hinged at the top, which pushes and draws the air confined in the chamber to rotate the turbine on it while the incoming waves swing the flap, as shown in Fig. 1. The chamber may be surrounded with the curving backwall, the partision walls and the coping in which the air duct locates. The cofiguration of backwall looks like those of common seawalls and of dykes.

The experiment in a 24 meter long, 0.6 meter wide and 1 meter deep wave channel with regular waves, showed 20 to 50 % of the incident wave power was converted to the air pressure power, as shown in Fig. 2. The conversion efficiency η_a of the vertical axis in the figure is that defined as

$$\eta_a = \frac{\bar{W}_a}{B \cdot \bar{W}_i} \times 100 \quad (\%) \qquad (1)$$

where $\bar{W}_i$ is the incident wave power per unit crest width and is given by the following equation for the regular waves.

$$\bar{W}_i = \bar{E} \cdot C_g = \frac{1}{8} w_o H^2 C_g \qquad (2)$$

where C_g is the group velocity of the incident wave. $\bar{W}_a$ is the average air pressure power absorbed by the system of length B and is estimated as

$$\bar{W}_a = \frac{1}{T} \int p \cdot dV \qquad (3)$$

where T is the wave period, p is the air pressure and V denotes the volume of air in chamber.

The effect of the opening ratio of air duct e is not clear. There are two apparent peaks of the efficiency, for $T/T_N = 1.5$ and 2.1. T_N is the natural period of the pendular.

Because of the efficiency of model air turbine being low, torque of air turbine remains about 2 % of the regular incident wave power. This figure, of course, will be much improved by employing a more efficient air tubine.

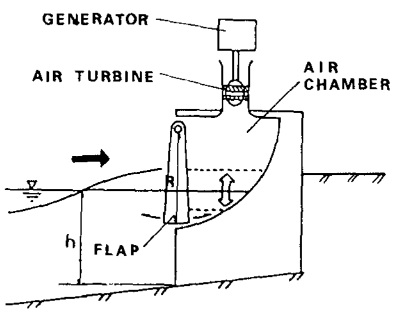

FIG.1 SKETCH OF AIR CHAMBER WITH FLAP

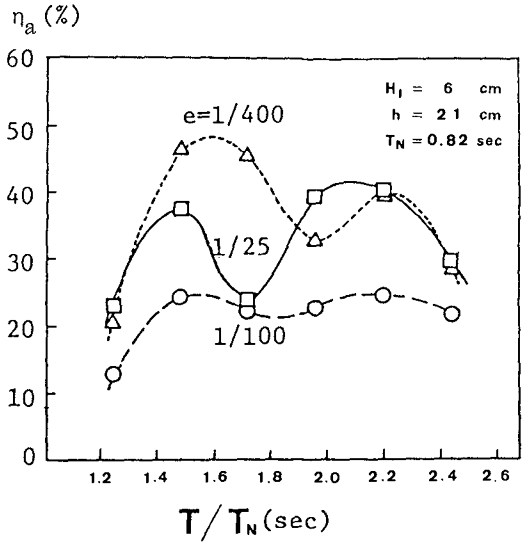

FIG.2 CONVERSION EFFICIENCY FROM WAVE TO AIR

3 WAVE TURBINE SYSTEM

The next system has a three-vane Savonius turbine rotating around the vertical axis fixed in the rectangular water chamber formed in the reinforced concrete caisson without the seaward wall as seen in Fig. 3. The plane form of the turbine is asymetric in order to rotate it in the same direction in spite of the reciprocating wave force acting on it. The guide plates are attached to the partision walls and aim to concentrate the flow near the turbine and eventually to increase the torque of it. A standing wave occurs in the chamber. Thus the highest conversion efficiency is expected where the distance between the axis and the backwall is about the one quarter of the wave length in the chamber. That means the axis lies near the node of the standing wave. For the cases of relatively larger wave length, the caisson may be installed on a solid or a rubble base mound to decrease the depth of chamber, in which case the wave length becomes short so

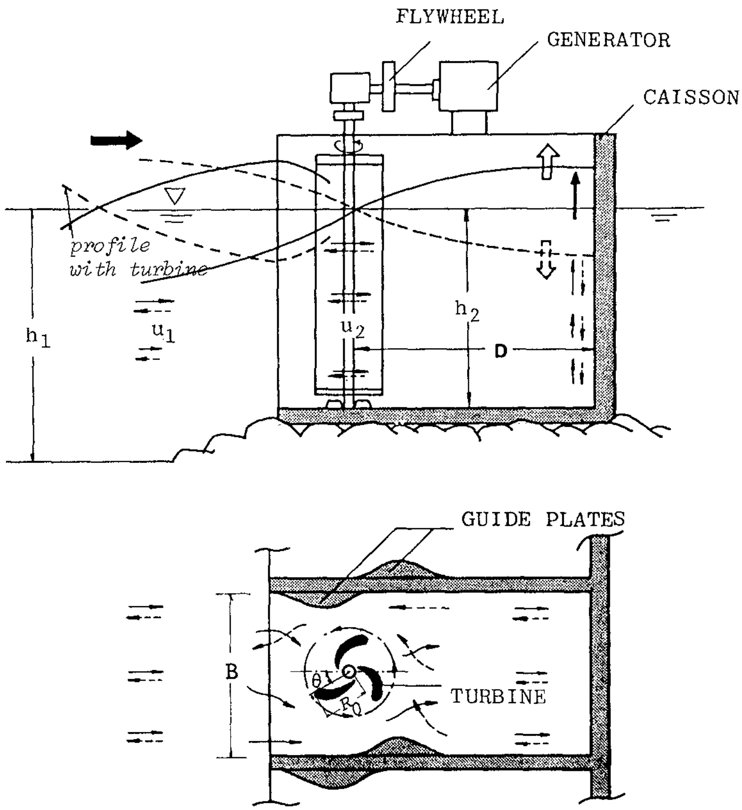

FIG.3 SKETCH OF WAVE TURBINE SYSTEM AND WATER PARTICLE MOTION AROUND IT

that the caisson width can be decreased for the given wave period and for the original depth h_1.

The experiment was performed for the power extraction, wave reflection and wave force characteristics of the system in the same channel described in the section 2. The details of the result had been reported by KONDO et al.(19 80, 1981). The average power extracted by the turbine $\bar{W}_t$ was evaluated by

$$\bar{W}_t = \tau\,\bar{\dot{\theta}} \qquad (4)$$

where τ is the load torque and $\dot{\theta}$ is the angular velocity of turbine. The conversion efficiency η_t from incident wave power to torque of turbine of length is defined as

$$\eta_t = \frac{\bar{W}_t}{B \cdot \bar{W}_i} \times 100 \ (\%) \qquad (5)$$

The actual efficiency of mechanical conversion for the system with $h_1 \neq h_2$ in which a part of incident wave power is reflected, should be defined as

$$\eta_e = \frac{\bar{W}_t}{B \cdot \bar{W}_i'} \times 100 (\%) \qquad (6)$$

where $\bar{W}_i'$ is the transmitted wave power into the chamber per unit crest width without the system. η_e should be η_t for the case $h_1 = h_2$. The efficiency η_e takes the maximum for the relative distance of axis from backwall D/L around 0.25 as expected, which can be seen in Fig. 4. The guide plates are much effective to increase the extracted power as shown in the figure. However, η_e remains 20 % at most. The theoretical values of η_e shown with solid and broken lines in the figure were those of calculated with the approach presented in the Appendix.

The reflection coefficient of the structure as a whole is almost less than 0.4 and is comparable to that of common rubble mound breakwaters. Fig. 5 prensents the critical wave height to slide the caisson with the system, from which the horizontal wave force against the structure as a whole is estimated to be 50 % or less of that on the impervious upright breakwaters.

4 PENDULOR SYSTEM

The last system has an oscillating pendulor around the horizontal axis perpendicular to it, and transmits the power of pendulor to that of oil pressure through the reciprocating cylinder connected to the pendulor at the top, as illustrated in Fig. 6.

The experiment had been performed on the horizontal bottom in a 18.5 meter long, 0.4 meter wide and 1 meter deep wave channel at the initial stage and later in the 24 meter channel stated in the section 2. The average power extracted to the oil pressure was determined in the experiment by

$$\bar{W}_p = \frac{1}{T}\int F_c\, r_c\, \dot{\theta}\, dt \qquad (7)$$

where r_c is the distance between the neutral position of pendular and the center of cylinder, and $\dot{\theta}$ is the angular velocity of pendulor. F_c is the reaction force of cylin-

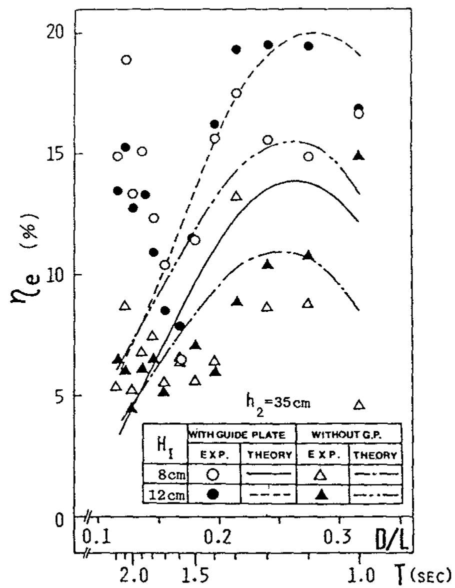

FIG.4 CONVERSION EFFICIENCY FROM THE TRANSMITTED WAVE POWER INTO THE CHAMBER TO THE TORQUE

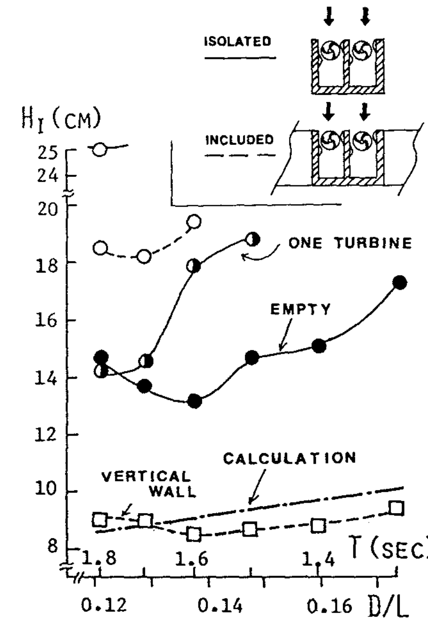

FIG.5 CRITICAL INCIDENT WAVE HEIGHT FOR SLIDENG OF CAISSON

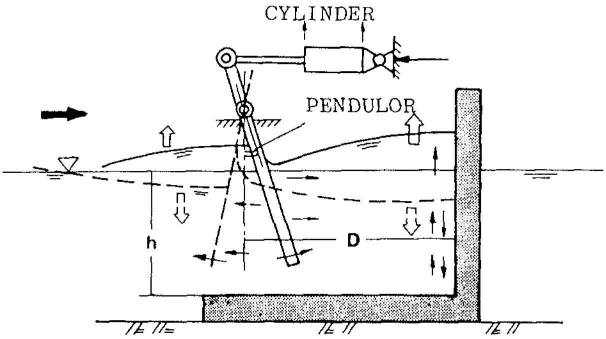

FIG. 6 SKETCH OF THE PENDULOR SYSTEM

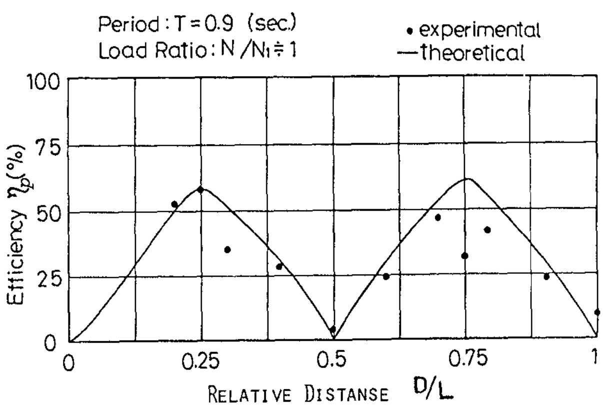

FIG. 7 CONVERSION EFFICIENCY FROM WAVE TO OIL PRESSURE VERSUS RELATIVE DISTANCE OF THE PENDULOR AXIS FROM BACKWALL

der and is evaluated as

$$F_C = F_O + \beta(r_C\dot{\theta})^2 \qquad (8)$$

where F_O is the frictional force of cylinder and β is the load coefficient due to the orifice restrictor. Then the conversion efficiency of the system with length B is

$$\eta_p = \frac{\bar{W}p}{B\cdot\bar{W}_i}\times 100 \quad (\%) \qquad (9)$$

The system also brings the maximal of η_p where the neutral position of pendulor coincides the location of node of the standing waves formed in the chamber, as clearly seen in Fig. 7. The maximum value of η_p was 80 % in the experiment . The two dimensional analysis for the small amplitude wave had been derived by Asano (1980), outline of which will be introduced in the paper by Ando et al. (1984). Fig. 8 presents the result of comparison of theoretical efficiency with experimental one. The theory successfully predicts the experimental data or the cases of relatively lighter load condition and of shorter wave period, as shown in Fig. 8.

5 FIELD EXPERIMENT

In order to investigating feasibility of the last two systems at the sea, a series of the field test has been carried out employing a test caisson. It is 6.1 meter long,

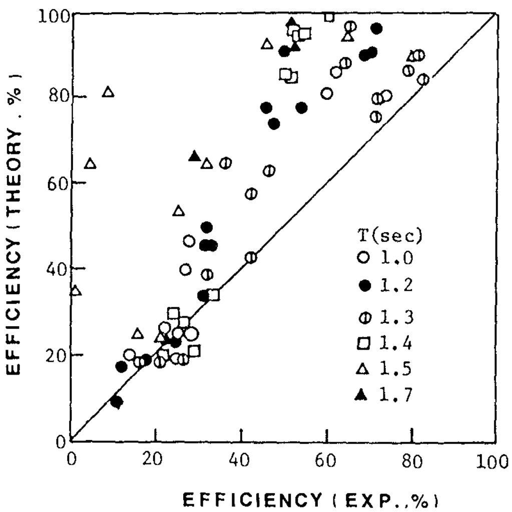

FIG.8 COMPARISON OF THE EFFICIENCIES OF THEORY AND OF EXPERIMENT

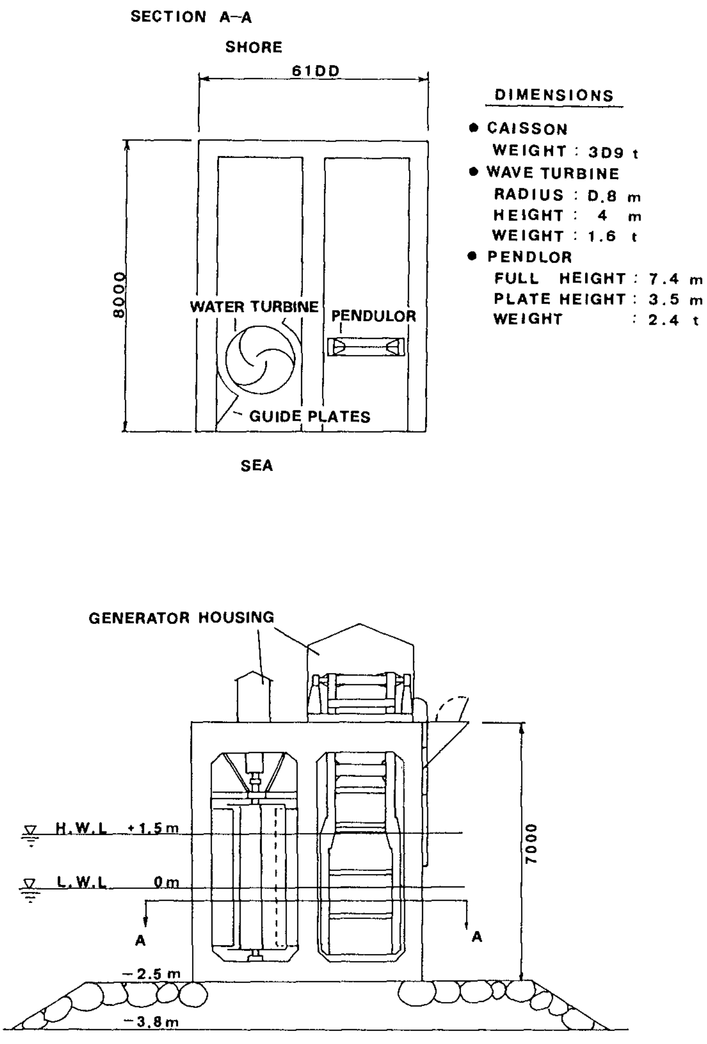

FIG.9 THE FIELD TEST PLANT AT PORT MURORAN

Photo. 1

Test Plant Caisson befor installation - Wave Turbine and Guide Plates had been set in the left hand side Chamber

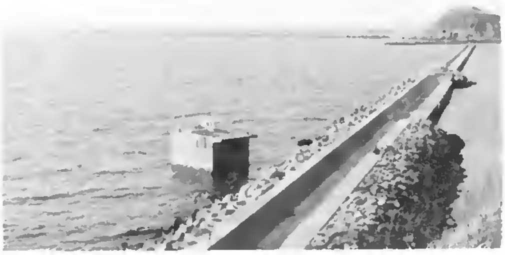

Photo. 2

Test Plant just after installation at seaward of South Breakwater of Port Muroran in April 1980

Photo. 3

The Pendulor is being set in the another Chamber of Test Plant in March 1983

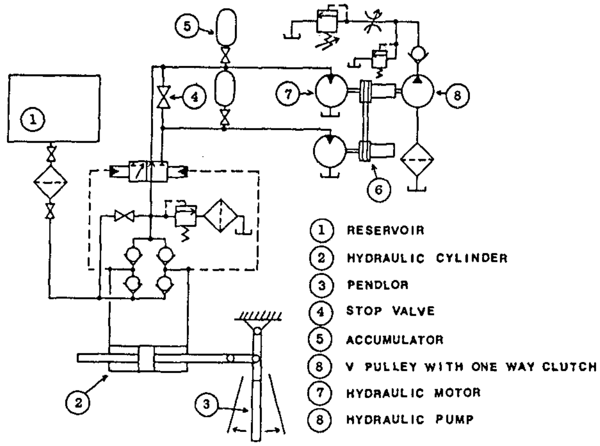

FIG.10 THE OIL PRESSURE CIRCUIT OF TEST PLANT

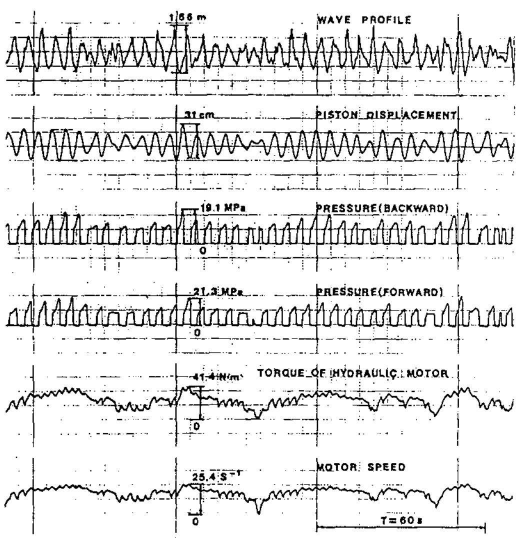

FIG.11 EXAMPLE OF THE DATA MEASURED AT TEST PLANT

7 meter high and 8 meter wide, and had been constructed seaward of the south breakwater of Port Muroran in the spring of 1980 (see Fig.9 and Photo.1 and 2). As seen from Photo. 1, the caisson has two chambers to be able to install two kinds of systems. Since the port faces to a bay on the Pacific south west coast of Hokkaido Island, the waves of $H_{1/3} \geq 1.0$ meter is approximately 12 % and appear mostly in winter.

The power extracted by the wave turbine system at the caisson transmits via a flywheel to the 2 kW D.C. generator. The extracted power measured in front of the generator was in the range of 3 to 8 % of the incident wave power, and much fluctuated. The incident wave power of the sea waves was estimated with the following equation to the Bretschneider-Mitsuyasu spectrum, provided that the waves belong to those of deep water.

$$\bar{W}_i = \int_0^\infty S(f) \cdot C_g \cdot df = 0.44 \cdot H_{1/3}^2 \cdot T_{1/3} \ (kW/m) \qquad (10)$$

where $S(f)$ is the frequency spectrum, and $H_{1/3}$ and $T_{1/3}$ are the significant wave height and period, respectively. About 60 % of the torque power was converted to the electric power. The wave data used were of 2 km offsore.

The pendulor system which had been installed in the another chamber of caisson in 1983 is of 2.5 ton of weight and the length from the rotational axis to the lower end is 7.1 meter, as shown in Fig. 9. The plate to receive wave force at the lower part of it is 2 meter wide and 3.5 meter high (see Fig.9 and Photo.3). The secondary conversion block consists of the oil circuit which outputs the oil pressure with employing an oil pump instead of a generator which is illustrated in Fig. 10. The circuit can be used in the three ways, namely, the smoothing, the nonlinear and the linear ones, respectively. Fig. 11 presents an example of the measured data of the pendulor system. The

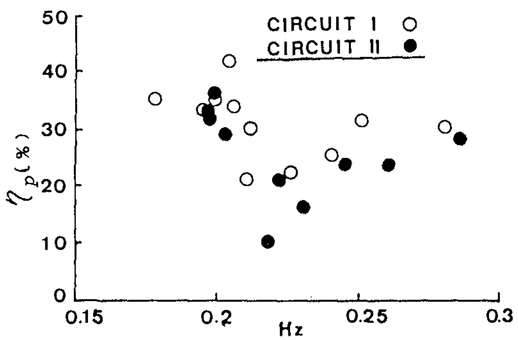

FIG.12 CONVERSION EFFICIENCY VERSUS WAVE FREQUENCY OF THE FIELD TEST

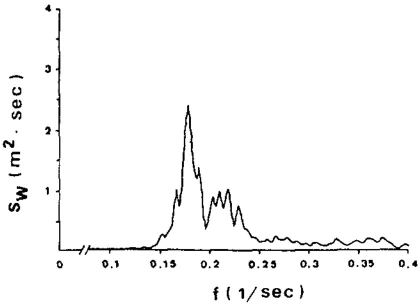

FIG.13 WAVE SPECTRUM SEAWARD OF THE CAISSON

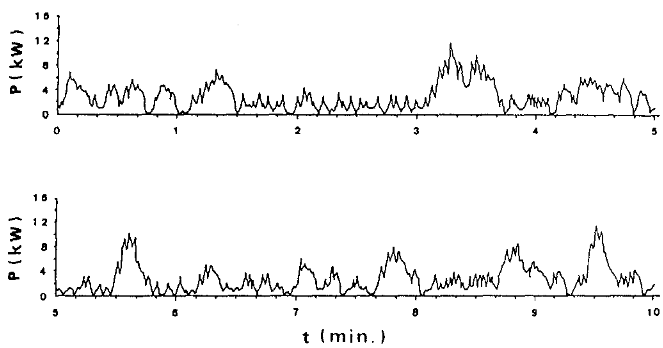

FIG.14 TIME HISTORY OF EXTRCTED OIL PRESSURE POWER

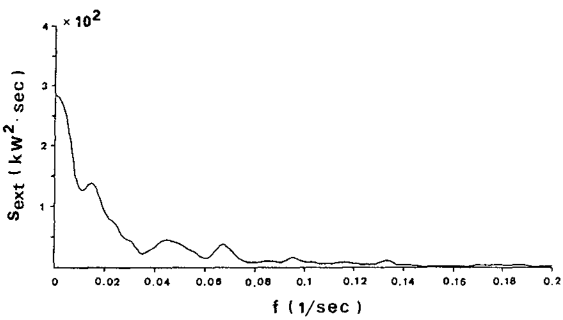

FIG.15 THE SPECTRUM OF THE EXTRACTED POWER

circuit I (smoothing) gave higher efficiency than the circuit II (nonlinear) did as shown in Fig. 12. The pendulor system with the smoothing circuit could convert about 35 % of the incident wave power to the oil pressure power. This figure seems to be a remarkably higher value as the data in real sea.

Figs. 13, 14 and 15 give examples of the wave spectrum from the datum measured 5 meter apart from the caisson with the ultrasonic wave gage set over the water surface, the time history of extracted power, and the spectrum of extracted power, respectively. The extracted power is much smoothened with the aid of the smoothing circuit.

6 CONCLUDING REMARKS

The cost of elecricity to be produced by the pendulor system in prototype commercial plant is estimated to be approximately 26 Yen/kWh or 11 US cents/kWh at the price of the year of 1982 in Japan, provided the average incident wave power $\bar{W}_I$=25 kW/m and the overall efficiency 20% (Ref. 5)). This figure can be reduced to about 60 % of that for the cases of construction cost of caisson being exempted, which may occur when it serves also as any breakwater, dyke or revetment. The pendulor system seems to be one of the most prospective wave power extractors, though there remains several engineering problems to be solved before the commercial use.

A small pilot plant of the pendulor system has been operated at Mashike Town, in the Japan Sea coast of Hokkaido, the details of which will be reported by Ando, et al.(1984).

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APPENDIX - The Simplified Analysis of the Power Extraction for the Wave Turbine System

The dynamic equation for the wave turbine of vertical axis set in the chamber as illustrated in Fig. 3 can be expressed as

$$(I + I_a) \ddot{\theta} + N_w \dot{\theta} + k\theta = \tau_w - \tau \qquad (11)$$

where I is moment of inertia of the turbine, I_a added moment of inertia, N_w damping coefficient due to radiation waves generated by the turbine, k restoring coefficient of the turbine, τ_w wave exciting torque on the turbine, τ torque of load, θ rotational angle of the turbine. The dot denotes the time derivative.

The torque τ_w on the turbine such as shown in Fig. 3 is approximated as

$$\tau_w = \rho C_t u_2^2 R_0^2 h_2 /2 \qquad (12)$$

where ρ is the density of fluid and C_t coefficient of torque on the turbine.

The horizontal water particle velocity u_2 is expressed as

$$u_2 = U_2 \cos(\sigma t - \delta) \qquad (13)$$

Then, the time average of τ_w in Eq.11 is given by

$$\bar{\tau}_w = \rho R_0^2 h_2 U_2^2 C_t /4 \qquad (14)$$

The load torque τ may be expressed as

$$\tau = N_t \dot{\theta} + \tau_{to}$$

where N_t and τ_{to} are the coefficients related to load resistance. Since the coefficient k may be relatively small for the system, Eq.11 becomes

$$\ddot{\theta} + p\dot{\theta} = r\cos 2(\sigma t - \delta) + s \qquad (15)$$

wh

$$p = \frac{N_w + N_t}{I + I_a}, \quad r = \frac{\bar{\tau}_w}{I + I_a}, \quad s = \frac{\bar{\tau}_w - \tau_{to}}{I + I_a}$$

The solution of Eq.15 is given as follows.

$$\theta = \frac{r}{2\sigma\sqrt{4\sigma^2 + p^2}} \cdot \sin[2(\sigma t - \delta) + \gamma] + \frac{q}{p}t + Ce^{-pt}$$

$$\text{where} \quad \gamma = \tan^{-1}\left(\frac{2\sigma}{p}\right) \qquad (16)$$

After calculating θ, the power extracted by the turbine is obtained with Eq.4 in secion 3. U_2 of Eq.4 may be approximated with wave deformation theory for the stepwise pervious structure by Kondo (1983).

REFERENCES

1) Ando, A., S. Ohtani, M. Takagi, M.Kuroi, H. Kondo, K.Yano and T. Watabe: On a flap type wave energy converter, Paper to be presented at ECOR International Conf.,1984.
2) Asano, S.: Energy absorption efficiency of flap type wave energy converter, JTTC, SK60-14, 1980(in Japanese).
3) Kondo, H.(Ed.): Study on the fixed type wave power generating systems to be installed in coastal structures, Rept. of Science Research Fund of Ministry of Education, 1978 - 79, 1980(in Japanese).
4) Kondo, H., K. Yano, M. Takahashi, T. Watabe and K. Okuda : A Device for wave power extraction in Coastal Structure - Wave turbine system-, Proc. of 28th Japanese Conf. on Coastal Eng., JSCE, 1981(in Japanese).
5) Kondo, H.(Ed.): Ocean Energy Utilization Technology, Research Rept., No.1, Hokkaido Port & Coastal Research Assoc., 1983(in Japanese).

6) Kondo, H.: Reflection and transmission of shallow water waves at the pervious coastal structures on solid step, Proc. of XX Congress of IAHR, Vol.VII, 1983.
7) Watabe, T., H. Kondo, K. Yano, H. Takeda and M. Kuroi: A device for wave power extraction in coastal structure (2) -Pendulor system-, Proc. of 29th Japanese Conf. on Coastal Eng., JSCE, 1982(in Japanese).
8) Watabe. T., H. Kondo and K. Yano: Wave energy conversion by wave pendulor - Design of experimental plant outside the Port of Muroran, Proc. of JSME, in press (in Japanese).