HYDRAULIC TECHNOLOGY AND UTILIZATION OF OCEAN WAVE POWER

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ABSTRACT

Utilization of ocean wave power is one of our dreams.

A system introduced here "Pendolor" has pendulums which resonate in the exciting wave motion and the pendulums drive a generator via hydrostatic drive system. We believe, this "Pendolor" would bring the dream in our life. The combination of the pendulum (mechanical power transfer) and the HST (hydraulic power transfer) gave 40% overall efficiency in ocean testing, having a basic matching of their huge thrust force -low speed features. The Pendolor absorbs wave force and makes little reflecting waves so effectively that the caisson attached it can become an improved breakwater.

25 yen/kWH or 9.4 yen/kWH are expected using a proto-type Pendolor designed here, including with or without caisson cost.

KEY WORDS

Fluid Power System, Ocean Engineering,
Systems Engineering, Power Plant.

NOMENCLATURE

A=constant expressed by E_q (8)
 A_p =area of the cylinder
 B=constant expressed by E_q (9)
 B_p =width of pressure plate of the Pendolor
 C_g =group speed of the incident waves
 d =water chamber length
 D_m =displacement of the motor
 E =wave energy entered to the Pendolor during time T
 f =frequency of the wave component
 g =acceleration of gravity
 H =wave height
 $H_{1/3}$ =significant wave height
 H =average wave height
 h =water depth
 ΣI =equivalent moment of Inertia of the Pendolor (including added water)

K =restoring coefficient due to water elevation behind the Pendolor
 K_c =constant
 K_a =restoring coefficient of the Paendolor
 l =distance from the swing center to surface of still water
 M =amplitude of exciting moment
 M_0 =reaction moment of the cylinder
 $\bar{M}_0$ =average value of M_0
 N =damping coefficient due to radiation waves generated by the Pendolor
 N_0 =equivalent linear damping coefficient by the cylinder
 n =oil motor speed
 P =wave power per meter crest
 $\bar{p}$ =average cylinder pressure of the delivery period
 Q =average flow from the cylinder
 r =arm length (see Fig.1)
 $S(f)$ =density function of frequency spectrum
 T =period of wave
 T =mean wave period
 T_m =average motor torque
 t =time
 V =oil volume trapped in the accumulator
 W =energy absorbed by the cylinder during T
 θ =angular displacement of the Pendolor
 θ_0 =initial extreme value of θ
 θ_a =amplitude of the Pendolor
 η =energy absorption ratio
 η_t =torque efficiency
 η_v =volumetric efficiency
 η_m =motor efficiency
 ρ =density of water
 λ =wave length
 ω =circular frequency of wave

PREFACE

The Problem in putting wave energy to practical use is whether the energy cost can be reduced to an acceptable level. In addition to the same excellent ability for wave power extraction as a modern machine, the system must be as simple as an ancient machine. However, it still seems difficult to find a way to reach a reasonable cost

target although many types of apparatuses have been proposed and studied in the world.¹⁾

A system combined with both a mechanical device for receiving wave power and an oil-hydraulic device for converting the power to an electric device has been developed by us. It is named the Pendulor system. By introducing hydraulic technology into the wave power utilization system, we can propose more adaptable and more flexible system to harness the wild wave power. One of them is the Pendulor system.²⁾

We have been studying it, including coastal operations for 10 years. Through our investigation, the system has proved its good reliability and high power extraction ratio using several test models featured by the design criterion developed at Muroran Inst. of Technology. The proto-type design of, and the study on, cost expectancy of the wave energy have been accomplished.

THE PENDULOR SYSTEM

Wave energy consists of two kinds of physical energy;---potential and kinetic. The Pendulor directly absorbs the energy as the Pendulor's swinging motion. As illustrated in Fig.1,

Fig. 1 Principle of the Pendulor System

incident waves are changed to standing waves by superposition with reflecting waves in the chamber. At the node of the standing waves, all energy is concentrated into horizontal reciprocating water flow. A pendulum with a pressure plate placed at the node "Pendulor", is driven by that flow. The Pendulor drives a cylinder, and then two hydraulic motors fed by the cylinder drive a generator. There is a phase difference of π between the two motors. As a result although the output torque of each motor varies periodically according to a wave's pause, the final output is made smooth by the superposition of the two.³⁾

The energy absorption ratio can be predicted by the following procedure. The Pendulor's motion is found by solving the Pendulor's equation of motion expressed in Eq. (1)

$$\Sigma I \ddot{\theta} + N \dot{\theta} + (K_0 + K) \theta + M_0 = M \sin \omega t \quad (1)$$

where M_0 is a reaction moment of the cylinder. It is written in the following form when the cylinder delivers oil to the circuits shown in Fig.1.

$$M_0 = - \{ M_{02} + K_c (\theta - \theta_0) \} \quad (2)$$

where M_{02} is the initial value of the reaction moment.

For absorbing maximum energy, M_0 should satisfy the following Eq.⁴⁾

$$W = \int_0^T M_0 \dot{\theta} dt = \eta \int_0^T N \dot{\theta}^2 dt \quad (3)$$

Furthermore, when the natural frequency of the Pendulor is adjusted to the same substantial value as the frequency of the standing waves, and when the Pendulor is hung vertically at the node, the cylinder absorbs almost all of the energy of the incident waves.⁵⁾ So the energy absorbed during T can be expressed as Eq. (4), in which the right term means the incident energy coming into the Pendulor during T.

$$E \eta$$

$$= \frac{1}{4} T B_0 \left(\frac{H}{2} \right)^2 \rho g \frac{\omega}{k_0} \left(1 + \frac{2 k_0 h}{\sinh 2 k_0 h} \right) \eta$$

$$= \int_0^T M_0 \dot{\theta} dt \quad (4)$$

The wave number $k_0 = 2\pi/\lambda$ must satisfy the dispersion relation $\omega^2/g = k_0 \tanh(k_0 h)$. With this optimal condition, the Pendulor is resonated, so that the phase difference between the exciting moment $M \sin \omega t$ and θ is fixed in $(-\pi/2)$. Since the Pendulor mostly absorbs the incident wave energy, it generates no reflecting waves.⁶⁾

Fig.2 shows the typical results obtained in our laboratory using a 1/6 scale model.

$$T = 1.4 \text{ s}, \quad \nabla k'_e = 5.0 \times 10^6 \text{ N/m}$$

$$\bullet = 5.0 \times 10^5 \text{ N/m}$$

$$\circ = 2.8 \times 10^5 \text{ N/m}$$

Fig. 2 Wave Power Absorption Ratio

AN OPTIMAL DESIGN OF THE HYDRAULIC CIRCUITS

In Chapter 2, the optimal condition for the Pendulor was explained when regular waves (having constant wave height and period) drive it. Next we have to consider the influences by the real open sea waves (having irregular wave heights and periods).

Sea waves can be observed as superposition of many different waves. Using average wave height $\bar{H}$, wave height H is described as Rayleigh distribution in the following Eq. (5),

$$p(H/\bar{H}) = \frac{\pi}{2} \left(\frac{H}{\bar{H}}\right) \exp \left[-\frac{\pi}{4} \left(\frac{H}{\bar{H}}\right)^2\right] \quad (5)$$

where $p(H/\bar{H})$ is a probability density function of wave height,

Fig. 3 shows $p(H/\bar{H})$ versus $H/\bar{H}$, while the function of wave period T is also shown there in comparison with it, using mean wave period $\bar{T}$.

The mean power per unit length of the wave crest P , was verified by Bretschneider & Mitsuyasu as the Eq. (6).⁷⁾

$$P = \rho g \int_0^\infty C_a S(f) df$$

$$= 0.441 H^2_{1/3} T_{1/3} \quad (6)$$

$$S(f) = A f^{-5} \exp[-B f^{-4}] \quad (7)$$

$$A = 0.257 H^2_{1/3} T^{-4}_{1/3} \quad (8)$$

$$B = 1.03 T^{-4}_{1/3} \quad (9)$$

Though the sea waves consist of a wide band of spectrum, Fig. 3 shows a peak distinguished in its distribution. Since the wave energy is concentrated around the peak component, a preferable energy absorption should be done as a regular wave operation, if the optimal condition is selected towards the peak. Any control devices are required to keep the optimal condition, by controlling M_0 and natural frequency of the Pendulor, because mean wave height $\bar{H}$ and mean wave period $\bar{T}$ vary day by day.

Fig. 3 Wave Spectra

At the optimal operation, the amplitude of the Pendulor θ_0 theoretically takes the value expressed by Eq. (10).⁸⁾

$$\theta_0 = \frac{k_0 Z_0}{4 Y_0 \sinh(k_0 h)} \cdot \frac{H}{2} \quad (10)$$

where

$$Y_0 = k_0 l \sinh(k_0 h) + \cosh(k_0 h) - 1 \quad (11)$$

$$Z_0 = \sinh(2 k_0 h) + 2 k_0 h \quad (12)$$

In order to maintain the optimal operation, the following procedure has been considered;

- 1) Reaction moment M_0 is controlled to keep the relationship between H and θ_0 expressed in Eq. (10).
- 2) This can be done by the energy conservation principle, if every energy absorbed by each stroke of the cylinder, would substantially correspond to the every energy of the waves driving the Pendulor one after another.

Fig. 4 shows the content of the idea mentioned above;--- it is a controlled moment M_0 which satisfies Eq. (3). The following equation can be written for the energy conservation.

$$W = 2 \int_{\theta_0}^{\theta_0} M_0 d\theta = \eta E \quad (13)$$

where θ_0 is expressed by Eq. (10)

In Fig. 4, W is shown as the area enclosed by M_0 curve, and so long as θ_0 is varied with H , the enclosures take form of triangles or rectangles. From Eq. (13), M_0 is described as follows.

$$M_0 = \frac{\pi}{4} \omega N \eta \theta_0 + \frac{\partial M_0}{\partial \theta} \cdot \theta \quad \text{when } \dot{\theta} < 0 \quad (14)$$

$$M_0 = -\frac{\pi}{4} \omega N \eta \theta_0 + \frac{\partial M_0}{\partial \theta} \cdot \theta \quad \text{when } \dot{\theta} > 0$$

where $\theta_0 \geq \theta \geq -\theta_0$

$$M_{02} = -M_{03} = \left(\frac{\pi}{4} \omega N \eta + \frac{\partial M_0}{\partial \theta} \right) \theta_0$$

$$M_{01} = -M_{04} = \left(\frac{\pi}{4} \omega N \eta - \frac{\partial M_0}{\partial \theta} \right) \theta_0 \quad (15)$$

M_0 shown in Fig. 4 can be obtained by connecting accumulators which have the pressure characteristics shown in Fig. 5, and the average delivery flow Q from the cylinder is controlled in a quantity shown by Eq. (16).

$$Q = 2 \theta_0 A_p r / T = D_m n / \eta_v \propto \bar{p} \quad (16)$$

then, displacement D_m of the motor becomes,

$$D_m = \frac{2 \theta_0 A_p r \eta_v}{T n} = \frac{8}{\pi} \cdot \frac{(A_p r)^2}{T n N \omega} \cdot \frac{\eta_v}{\eta} \bar{p} \quad (17)$$

where

$$\bar{p} = \bar{M}_0 / A_p r \quad (18)$$

Fig. 4 Reaction Moment M_O

Fig. 5 Characteristics of the Accumulators

Fig. 6 Block Diagram of the Optimal Operating System

Fig. 7 General View of the Test Pendulum

Fig. 8 The Wave Climate

Fig. 9 The Location Site

$$\bar{M}_e = \frac{1}{2} (M_{e1} + M_{e2}) \quad (19)$$

Fig.6 shows the principle of this optimal operation as a block diagram. When the motor drives a constant speed generator, the output is proportional to its average torque $\bar{T}_m$.

$$\bar{T}_m = \frac{\bar{P} D_m}{2\pi} \eta_t$$

$$= \left(\frac{2}{\pi} \cdot A_p r \bar{P} \right)^2 (T_n N \omega)^{-1} \frac{\eta_m}{\eta} \quad (20)$$

There are two negative feed backs in Fig.6; --- flow of the motor and damping by the cylinder, so the output is balanced at a level tracing to the incident energy level.

This system needs no any complicated devices such as wave sensor, computer etc. except only wave climate data observed at a near site where the Pendulor is placed.

EXPERIMENTAL OPERATION

We made a Pendulor device illustrated Fig.7 in which the main specifications are described there.

They were decided in terms of the wave climate data shown in Fig.8 which were measured off shore one kilometer away from the experimental site. It is in front of an outer dike of Muroran Port faced to the bay of Uchiura (See Fig. 9). Fig.10 shows that the Pendulor is going to set at the site.

The Pendulor has been operating there since 1983 and Fig.11 is a typical oscillogram recorded under as much the incident energy as 5 times level of the design point. In the Figure, cylinder pressure P_1 and P_2 appeared with two lines of saw edges-like, because of the accumulators of which the characteristics are similar to Fig.4 and 5. In spite of a big fluctuation of P_1 and P_2 , the fluctuation does not affect the output torque and the speed of the motor so much as seen in Fig.11. The output of the motor was 18~35 kW (on the average 24 kW), while the incident wave power was about 55 kW.⁹⁾

Fig. 10 Photo. of the Test Pendulor

Fig. 11 Typical Oscillogram

As explained previously, the energy absorption ratio η depends upon the period T and the reaction moment M_0 . Since the test Pendolor was designed to $T=4.0$ s, it can be resonated with waves having longer period than 4.0 s. In fact, the Pendolor has proved its ratio η high when $T \geq 4.0$ s.

Fig. 12 shows η of the test Pendolor versus load ratio N_0/N , where N_0 means an equivalent linear damping coefficient by the cylinder,

$$N_0 = \frac{1}{T} \int_0^T \frac{M_0}{\dot{\theta}} dt \quad (21)$$

The energy absorption ratio η was calculated using several measuring data, which have wave data more than 200 of the recording even at one measuring interval. Here η is defined as Eq. (22)

$$\eta = \frac{\frac{1}{t_0} \int_0^{t_0} M_0 \dot{\theta} dt}{P B_p} \quad (22)$$

where t_0 is measuring interval for a datum.

The Pendolor shows a peak in η curve near $N_0/N=1$ portion where η takes about 70 %. The white circles in Fig. 12 are in the case that M_0 is similar to Fig. 4.¹⁰⁾ and they are better than black circles.

Fig. 12 Wave Power Absorption Ratio

A STUDY ON COST EXPECTANCY

Considering cost efficiency, the apparatuses must be installed at the sites where they can get some economic merits because of its good energy density. For instance, the coastline faced to Norwegian sea in Europe and the places around Cape Town in Southern Africa have as much annual mean energy flux as 20~40 kW/m.¹¹⁾ However, we tried to make a design of a proto-type Pendolor for the cost study. Fig. 13 and 14 show the hydraulic circuits and the general view of the proto-type Pendolor. In this case, 10.6 kW/m was adopted as the annual mean energy flux corresponding to with $H_{1/3}=2$ m and $T_{1/3}=6$ s.

A 25 m wide caisson is used as a unit and three water chambers including a 7 m wide Pendolor each in it are prepared. So the total wave power coming into a unit becomes 222 kW, and the output; 88 kW of electric power, can be estimated adopting $\eta=40\%$ to the case of an annual mean power. The capacity of the generator being 90 kW for rating and 150 kW for peak has been selected in Fig. 13 & 14. In order to drive the generator, 6 H.S.T. units combined with cylinders and motors are provided. The motors adopted here are in one of the most familiar sizes for commercial use.

The caisson can be more stable against the waves, because the Pendolor absorbs the wave force as an extrating wave energy. Moreover, the Pendolor hardly makes reflecting waves, and the caisson

should be useful as a breakwater. Table 1 shows the results derived from this case study, in which it is supposed that 10 units of the caisson are set in a row as a 250 m long dike.¹²⁾

In Table 1, the caisson cost per unit length is 6 million yen/m, the generator is 8.5 million yen/unit, cylinder is 1 million yen/u are estimated. The life expectancy being 50 years for the caisson and 15 years for the Pindolor is adopted for this estimation of the cost with 90 % of the operating period under the annual mean wave energy.

The cost of electricity is 25 yen/kWh when all the cost of the caisson is added to it. If we can utilize a breakwater as a facility of power generation, the cost of electricity will reach a very attractive level without the cost of caisson; --- 9.4 yen/kWh would be predicted.

CONCLUSIONS

By combining with a mechanical and oil-hydraulic technology, more adaptable and more flexible systems become feasible to utilize ocean wave power. The Pendolor is an example.

The optimal conditions of the Pendolor are expressed as follows

- (1) the Pendolor is placed at the node,
- (2) load ratio $N_0/N \approx 1$,
- (3) the Pendolor is driven at the resonance.

Maximum value of the absorption ratio obtained by the experiments is 70 % with both model and plant tests.

The Pendolor improves the stability of caisson and the reflecting waves.

Cost of electricity generated by a 250 m long caisson (attaching the Pindolors), would expect 25 yen / kWh or 9.4 yen / kWh with or without caisson cost, when the system is driven by the waves having an annual mean energy flux = 10.6 kW/m.

We have already patented the Pendolor system in UK, USA, Canada and Japan.

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Fig. 13 Hydraulic Circuits of the Proto-type Pendulor System

Fig. 14 General View of the Proto-type Pendulor System

Table 1 Cost of Electricity Generated by the Pendulor

Caisson = 250 m (25m unit × 10), Output = $\frac{1500 \text{ kW (max)}}{900 \text{ kW (rat)}}$	
<u>A</u> ;	Cost of Caisson = <u>1,500 million Yen</u>
<u>B</u> ;	Cost of the total System = <u>500 million Yen</u>
<u>C</u> ;	All Construction Cost = A+B = <u>2,000 million Yen</u>
C/Output = 2,000/1,500 = <u>1.33 million Yen/kW</u>	
" = 500/ " = <u>0.33 " " (without Caisson Cost)</u>	
<u>D</u> ;	Interest = C × 0.06 = <u>120 million Yen/Year</u>
" = " = <u>30 " " (without Caisson Cost)</u>	
<u>E</u> ;	Paying Prime Cost = B (1-0.1)/15 = <u>30 million Yen/Year</u>
<u>F</u> ;	Operating Cost = C × 0.01 = <u>20 million Yen/Year</u>
" = B × " = <u>5 " " (without Caisson Cost)</u>	
<u>G</u> ;	Current Expenditure = D+E+F = <u>170 million Yen/Year</u>
" = " = <u>65 " " (without Caisson Cost)</u>	
<u>H</u> ;	Amount of Absorbed Energy per Year
= 900 kW × 24 H/d × 320 d/year = <u>6912 MWH</u>	
<u>I</u> ;	Cost of Electricity = G/H = <u>25 Yen/kWH</u>
" = <u>9.4 " (without Caisson Cost)</u>	

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