# Utilization of the New Wave Power Convertor for the Improvement of the Marine Environment

Hitoshi HOTTA*1 Takeaki MIYAZAKI*1
Yukihisa WASHIO*1

In this report, the authors discuss the following three items.

Firstly, the method for estimation of the behavior and performance of the floating terminator OWC type wave power convertor are discussed in this paper. Theconvertor is moored at the offing and it can absorb the wave energy, convert it to a different form of energy, and create a calm sea area behind the device as a floating break water effectively.

Secondly, as an application of this method, authors have designed a new concept floating wave power convertor. It is "the Mighty Whale" and it has several unique behaviors. The outline of this device is introduced.

Finally, the concept of utilizing the wave energy, which is converting from wave to compressed air by "the Mighty Whale" is described. The authors propose that the wave power device should be used for improvement of the marine environment, because this energy is renewable and clean.

**Key words** : Ocean energy, Wave power, Wave power device,
Marine environment

* 1 Marine Development Research Department

## 1 INTRODUCTION

Ocean has several kinds of natural energy resources which are renewable and clean, and wave energy is the most convenient energy resources in the ocean. Because the total amount of the wave energy is very huge and we can utilize it at most part of the coastal zone except in the bay. However, the density of wave energy is not so high and the output of energy fluctuates with time. Nevertheless, the study on the utilization of wave energy is continued still now. Because, the wave energy will not occur any pollutions like $CO_2$ gas or acid rain.

Japan Marine Science and Technology Center carried out the open sea tests for two types of proto type wave power devices up to date. These are the floating attenuator type device "KAIMEI" [1) 2) 3)] and the shore fixed type device "SANZE" [4)]. As a result of the project of KAIMEI, we could confirm the possibility to utilize the wave energy, however the estimated value of the cost for the electrical generation was not so cheap and output power was not stable. In order to improve these shortcomings, JAMSTEC continued to research and succeeded to develop on the new type of the wave power device "the Mighty Whale ( Wave Height Absorbing Leisure Equipment)" [5)].

As a result of this research and development, it was clarified that the floating terminator OWC type device like FOWAD [6)] has most effective performance for the absorption of wave energy and the dissipation of the incident waves, if it will be moored at near coastline easily.

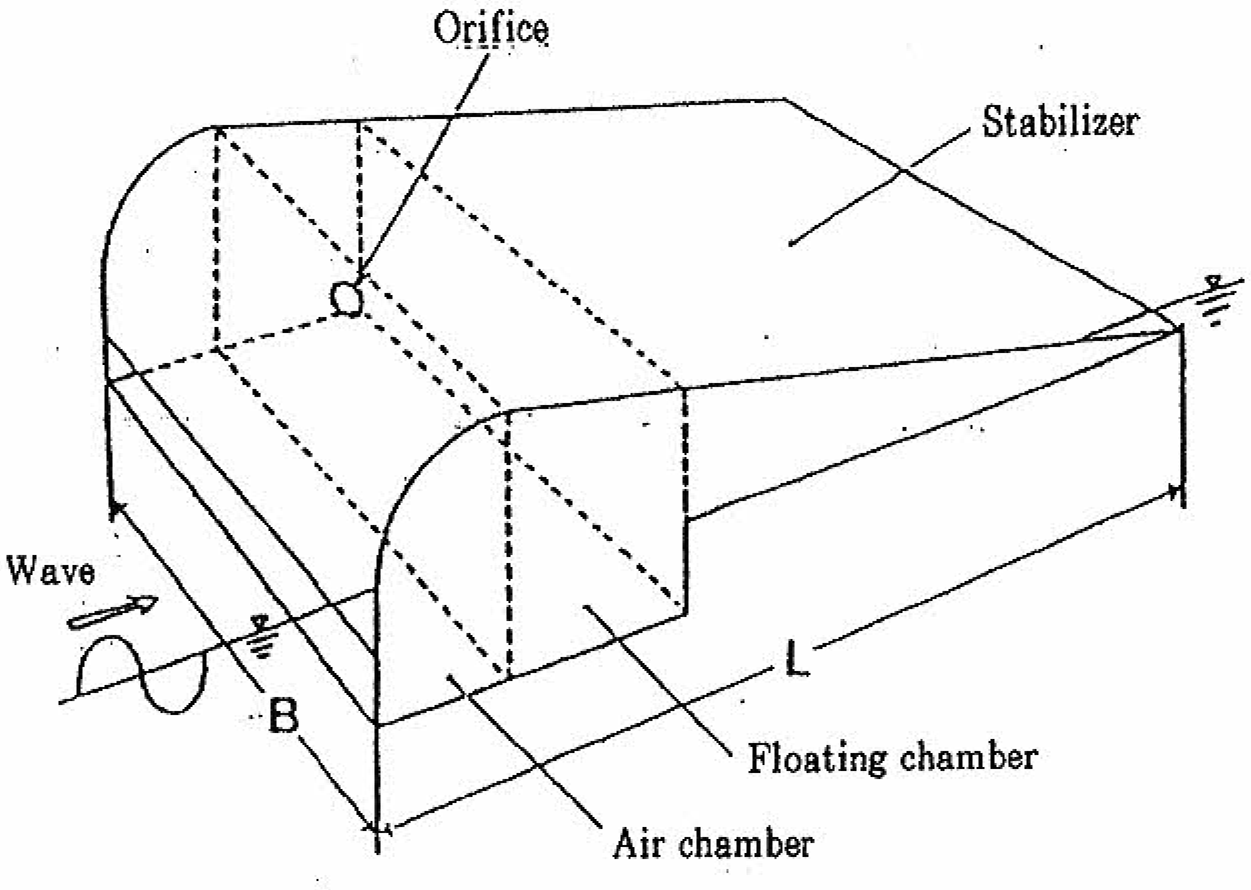
## 2 OUTLINE OF THE MIGHTY WHALE

The Mighty Whale has several air chambers which can absorb the incident wave energy and convert to the other energy resources. A floating chamber behind air chambers has the ability to keep the buoyancy. Every air chamber has an orifice and the air turbine generator on it, and it causes the damping force for vertical motion of the oscillating water column in an air chamber. Behind the floating chamber, a sloped plate is attached as the estabilizer and it creates an artificial beach which faces to natural beach for a marine leisure on it. A scheme of the Mighty Whale is shown in Fig. 1 .

Usually, the Mighty Whale is moored by some catenary chain lines, and its longitudinal axis coinsides to the significant direction of wave crests at the offing like a the floating break/water.

Most characteristic behaviors of the Mighty Whale are ;

(1) High efficiency of energy conversion from wave power to air power,
(2) High efficiency of dissipation of incident wave height,
(3) Small mooring force (Minus mooring force in some cases of wave frequency and wave height)




Principal dimension of the scale model

| | |
|---|---|
| Length | 0.7 m |
| Breadth | 0.49 m |
| Draft | 0.09 m |
| Depth | 0.20 m |
| Depth of curtain wall | 0.025 m |
| Weight | 5.5 kg |

Fig. 1 Scheme of the Mighty Whale

## 3 METHOD FOR ESTIMATION OF PERFORMANCE

### 3.1 Motion

When the Mighty Whale is moored and oscillates in the regular waves, since the coupling between heave and pitch and between sway, yaw and roll are remarkable rather than the coupling by the surge, the equations of six modes of motion should be considered under the condition of sea. However, in order to compare with the results obtained by the scale model test in the wave tank, we assumed that only three mode of motion, thes are heave, pitch and surge will occur in regular wave, that is a two dimensional condition. In such case, heave and pitch are described as follows.

$$M_{zz}\ddot{z}+(N_{zz}+N_{OWC,zz})\dot{z}+(C_{zz}+C_{OWC,zz})z +M_{pz}\ddot{\theta}+(N_{pz}+N_{OWC,pz})\dot{\theta} +(C_{pz}+C_{OWC,pz})\theta=F_z$$

$$M_{zp}\ddot{z}+(N_{zp}+N_{OWC,zz})\dot{z}+(C_{zp}+C_{OWC,zp})z +M_{pp}\ddot{\theta}+(N_{pp}+N_{OWC,pp})\dot{\theta} +(C_{pp}+C_{OWC,pp})\theta=M_\theta$$

And surge motion is described as follows.

$$M_x\ddot{x}+N_x\dot{x}+C_x x=F_x$$

where, $z$ ; vertical component (displacement)
$x$ ; horizontal component (displacement)
$\theta$ ; rotating angle of pitch motion
$p$ ; component of pitching
$M$ ; mass and inertia moment of device
$N$ ; damping force coefficient
$C$ ; restorering force coefficient
$F$ ; wave exciting force (moment)
$owc$ ; component due to OWC

In these equation, hydrodynamic force coefficients, such as added mass coefficients, wave making damping force coefficient and wave exciting force coefficients of each mode of motion are calculated by Ursel-Tasai method on a part of only air chamber with floating ch amber. And, total force which acts on the device is calculated by integration, that is the strip method. And, authors considered the stabilizer contributes for only viscous damping due to the eddy making at the edge of it.

Normally, the optimal breadth of the air chamber of such OWC type wave power device is about 15% of a wave length, and the optimal length of the floating wave power device is almost same as wave length[7]. Consequently, the author supposed that the stripe method is an available and convenient method to estimate the motion of the Mighty Whale even it has a "stabilizer" in waves. So, every term of differential equation were integrated along the londitudinal axis. However, it has several characteristics which the ordinaly ocean structure and ship do not have. These are the oscillating water column (OWC) in the air chamber, and large stabilizer. Consequently, the strip method have to be modified to apply to the Mighty Whale.

Strictly speaking, the mass of water in each air chamber changes at every moment because it is the OWC, and its surface is waving also. However, since such changes and effects due to such phenomena is not so large, it is available to neglect such items in this paper.

That means the mass of water (OWC) in the air chamber can be regarded as "the rigid body" which oscillates in the wave with the floating wave power device. Consequently, the total mass of the Mighty Whale should be considered as the mass of hull added the mass of OWC in each air chambers. Furthermore, it was considered that the restoring force caused by the displacement of the Mighty Whale is occured by the discharged volume of the hull and the OWC in each air chambers.

By the way, the damping force caused by the orifice on each air chamber must be considered and taken into the questions of motion. Because, the air chamber has a characteristics to absorb the wave energy efficiently and it generates a large damping force for vertical motion of the air chamber [8]. In this report, it was estimated as added damping force "D" which is assumed the linear damping force which is in proportion to the velocity of vertical motion of the OWC in each air chamber. So, the damping force due to the air chamber is

$$N_{OWC}\ \ddot{z} = D$$
$$= d_a A_W^2 (S_n C_n)\ \ddot{z}.$$

The coefficient of the added damping force "da" is [5],

$$d_a = 5 * \rho_a (A_W / (S_n C_n))\ \omega h_a$$

where $\rho_a$ ; density of water

$A_w$ ; sectional area of an air chamber

$S_n$ : area of an orifice

$C_n$ ; coefficient of constraction

$\omega$ ; angular velocity of wave

$h_a$ ; wave amplitude

### 3.2 Wave Power Absorption

For the estimation of wave power absorption by the Mighty Whale the author tried to apply "the thermodynamics and wave-kinematics method (TWM)" which was proposed by Takahashi et.al [7] for the estimation of efficiency of the wave power absorption, rather than "the equivalent floating method". However, since the Mighty Whale is oscillating in the waves, TWM should be modified in order to consider on the effect due to the oscillation and the floating device. The thermodynamics and wave-kinematics method is following method.

When an air chamber is fixed in the waves there is a following relation between amplitude and phase of incident waves and oscillation of OWC in the air chamber.

$$h_a = \frac{1}{2} h_{OWC} [\{ \alpha_o f(kh, kd_c) \sin \omega \tau \cdot \cos \omega \tau + kb \}^2 + \{ \alpha_o f(kh, kd_c) \cos^2 \omega \tau + \frac{kb}{\tan kb} \}^2 ]^{1/2} \quad (6)$$

$$\phi_{OWC} = -\tan^{-1} [-\{ \alpha_o f(kh, kd_c) \sin \omega \tau \cos \omega \tau + kb) / (\alpha_o f(kh, kd_c) \cos^2 \omega \tau + \frac{kb}{\tan kb}) \} \quad (7)$$

where, $h_{owc}$ ; amplitude of motion of OWC

$\phi_{owc}$ ; phase of motion of OWC

$k$ ; wave number

$h$ ; water depth

$b$ ; breadth of the air chamber

$d_c$ ; depth of the curtain wall

$\alpha_o = \kappa p_o / \rho_w g d_o$

$\kappa = C_p / C_v$

$C_p$ ; specific heat at steady pressure

$C_v$ ; specific heat at steady volume

$p$ ; atomospheric pressure

$\rho_w$ ; water density

$g$ ; gravitational acceleration

$d$ ; height of chamber on the water surface

$$f(kh, kd_c) = \frac{2 \cosh kh \sinh (h-d_c)}{\cosh k(h-d_c) \sinh k(h-d_c) + k(h-d_c)}$$

$$\omega \tau = \cos^{-1}(\sqrt{1+\beta^2} - \beta)$$

$$\beta = (C_n C_v \varepsilon_n)^2 (\kappa - 1) \frac{C_p T_o}{(\omega d_o)^2} \frac{d_o}{h_a}$$

$C_n$ ; coefficient of contraction

$C_v$ ; velocity coefficient

$\varepsilon_n$ ; nozzle ratio

$T$ ; absolute temperature of air

Using these equations and some equations on the energy of incident waves, we can derive the equation of efficiency of wave power absorption by the air chamber in regular waves as follows

$$\eta = \frac{\kappa \rho_o}{\rho_w g d_o} \frac{b\omega}{C_g} \cdot \frac{h_{OWC}}{h_a} \sin \omega \tau \cos \omega \tau$$

where $C_g$ ; group velocity of wave

$T_w$ ; wave period

Since the air chamber oscillates in waves, it is neccessary to correct the incident wave height "$h_{ri}$" in order to be availabel to TWM. In this report, the relative wave height at each air chamber was calculated by response and phase of motion of the Mighty Whale as following equation.

$$h_{ri} = h_a \cos\{\omega t - (l_i + x_i) k \cos \xi - y_i k \sin \xi\} - z_i$$

where, $h_a$ ; incident wave amplitude

$l_i$ ; distance between center of device and each air chamber

$x_i, y_i, z_i$ ; displacement of each air chamber

$\xi$ ; incident angle of wave

## 4 RESULTS OF MODEL TEST AND CALCULATIONS

The scale model test was carried out in a wave tank under the condition of two dimension. We supposed the scale of this model was about 1/100. In the test, incident wave and transmitted wave, 2 modes of motion (heave and pitch), air pressure in the air chamber and tension of a mooring line of weather side were measured.

As some results of the calculation and the scale model test, the characteristics of heaving and pitching motion of the Mighty Whale in regular waves (head sea) are shown in Fig. 2 and Fig. 3, transmitted wave height ratio is shown in Fig. 4, behavior of mooring force is shown Fig. 5, and the performance of wave energy absorption in regular wave is shown in Fig. 6.

By the comparison of the results of calculation and model test, we could confirm that the method for the estimation explained before in this paper is available to estimate heave motion and the efficiency of wave energy absorption, except pitch motion. We guess the reason of difference of pitch motion is effectad by the value of viscous damping due to the stabilizer.

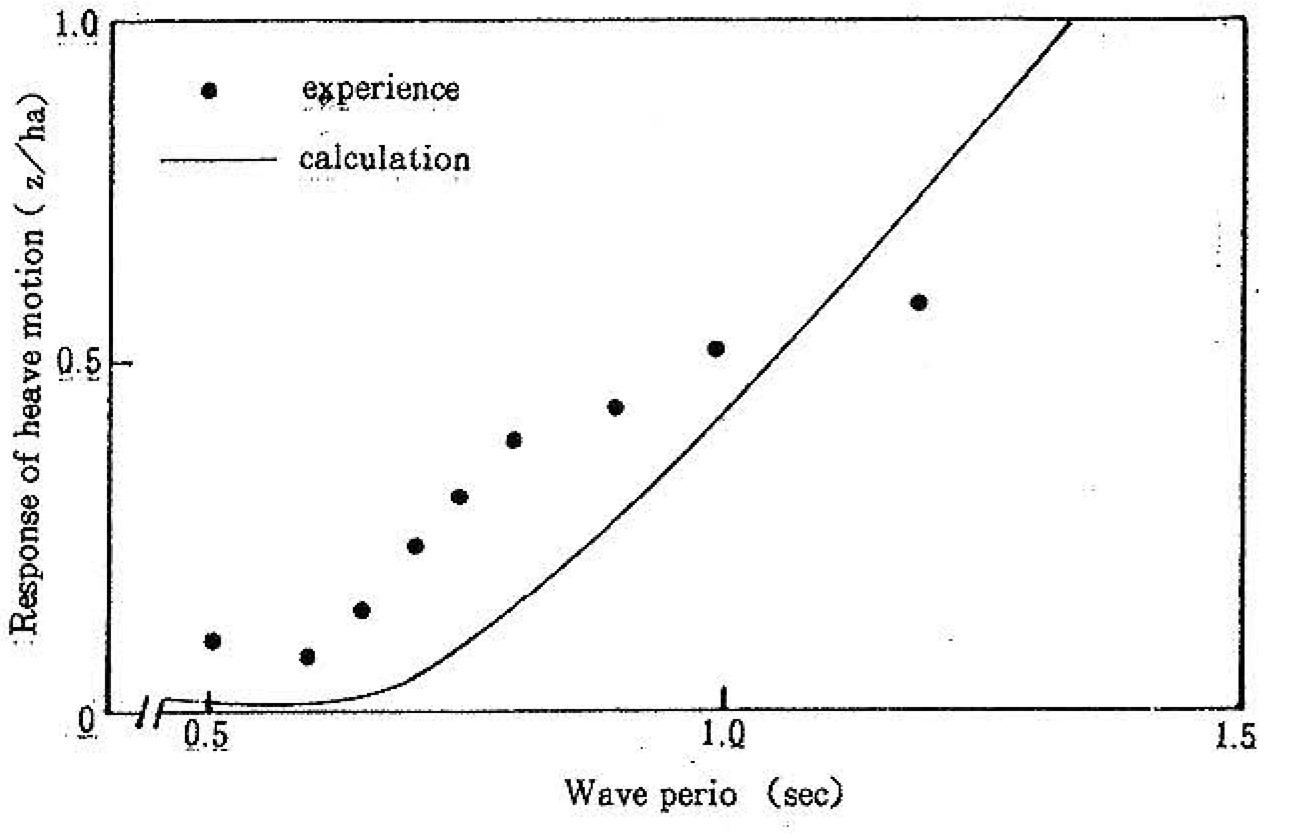



Fig. 2 Heave motion in regular waves

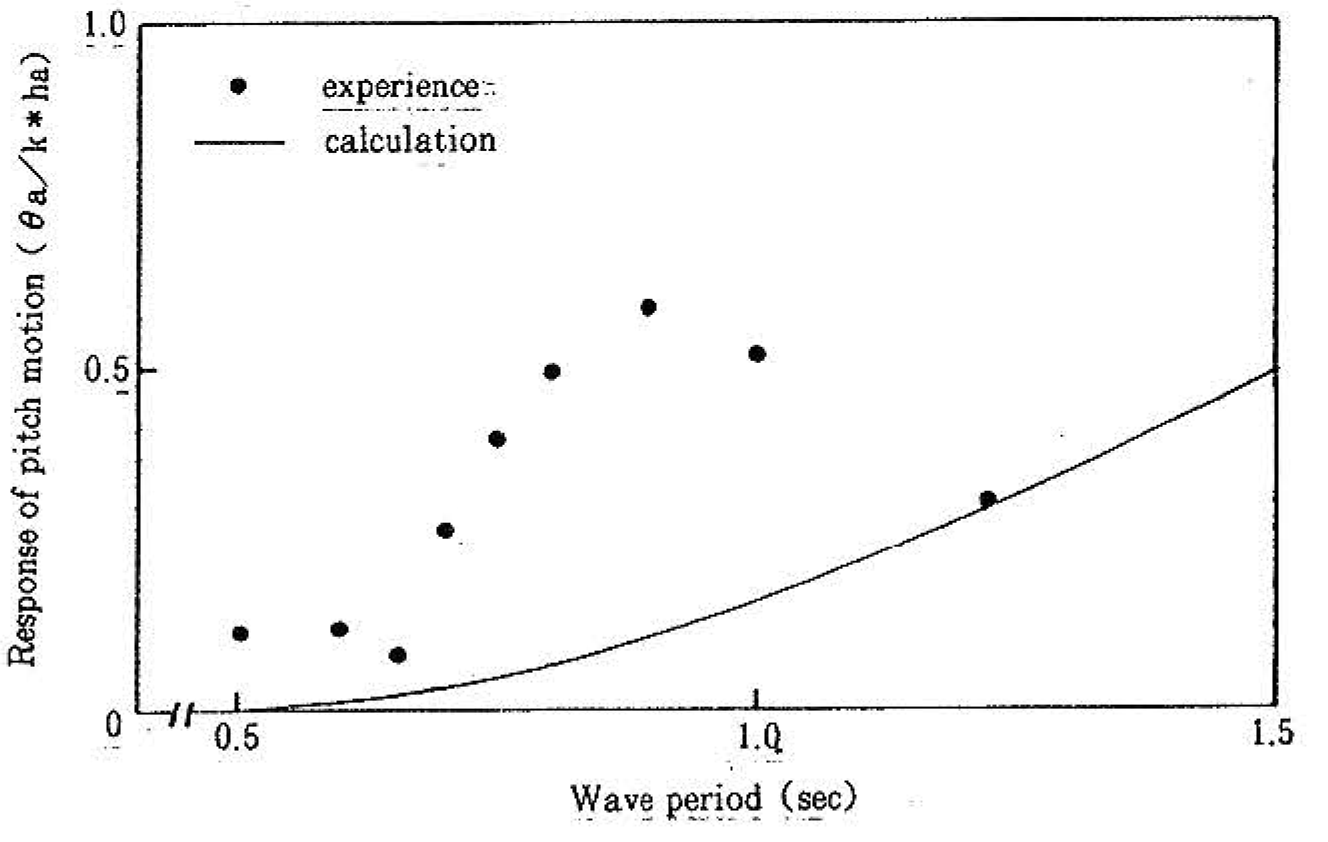



Fig. 3 Pitch motion in regular waves

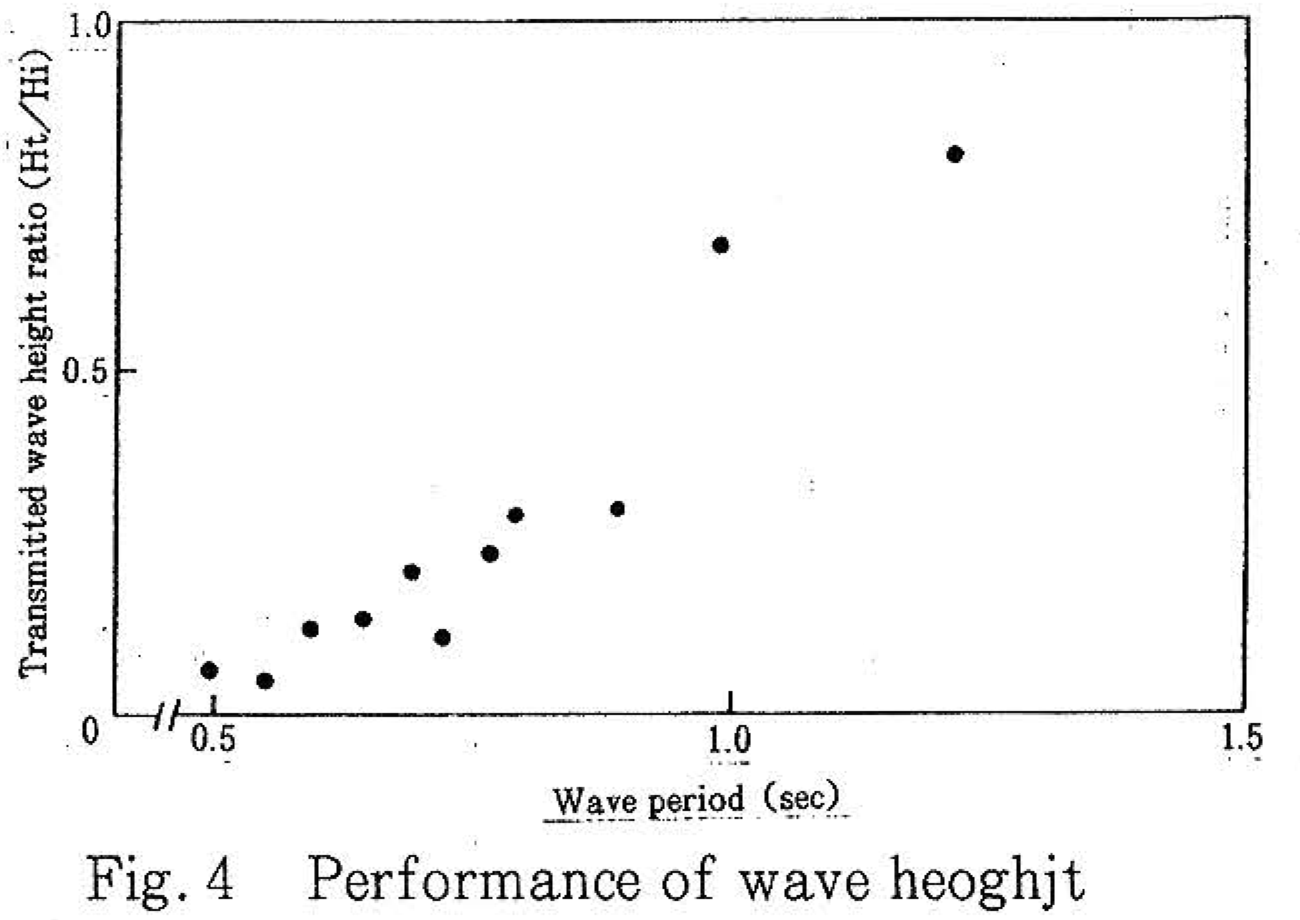



Fig. 4 Performance of wave heoghjt dissipation by the Mighty Whale

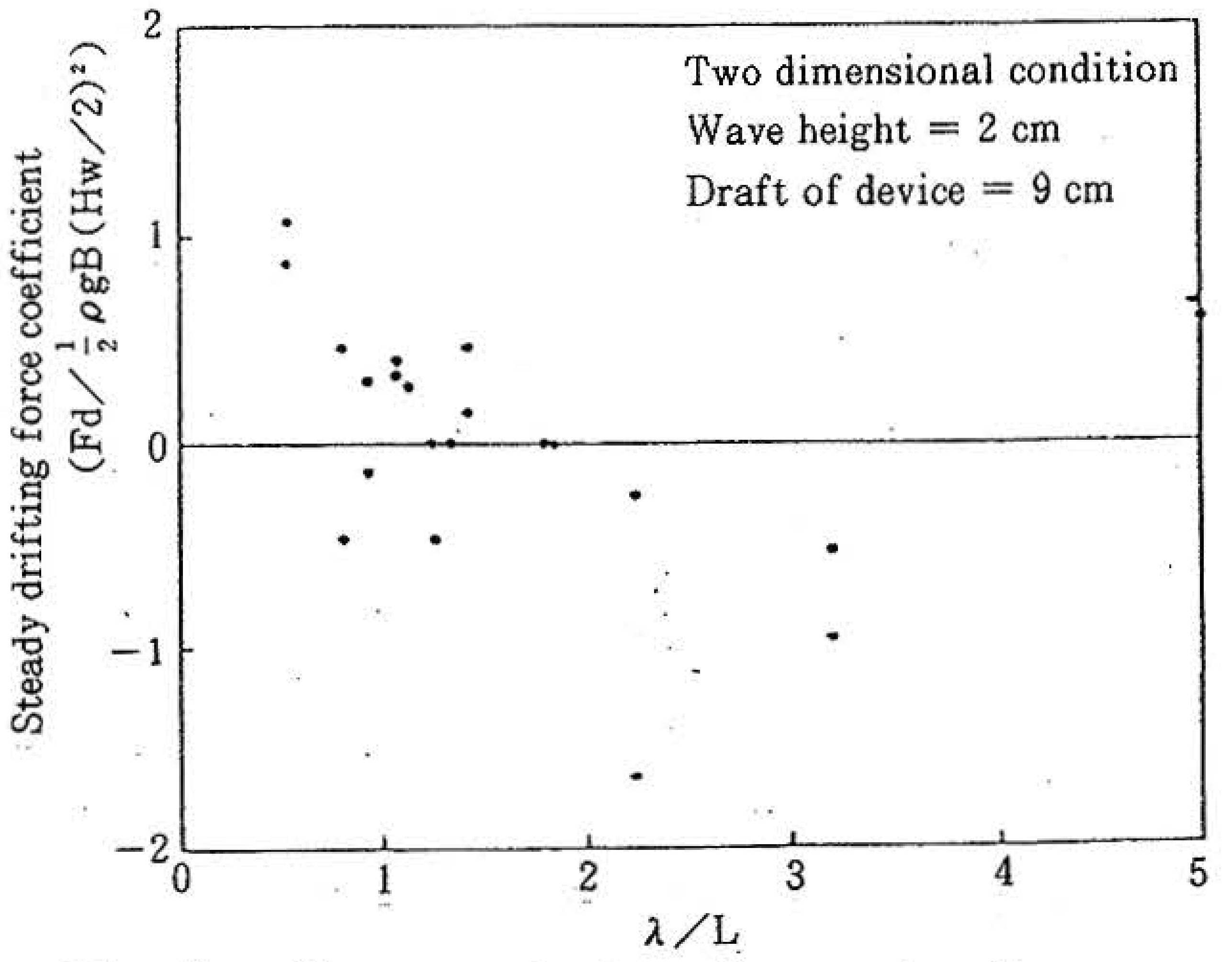



Fig. 5 Characteristics of mooring force of the Mighty Whale

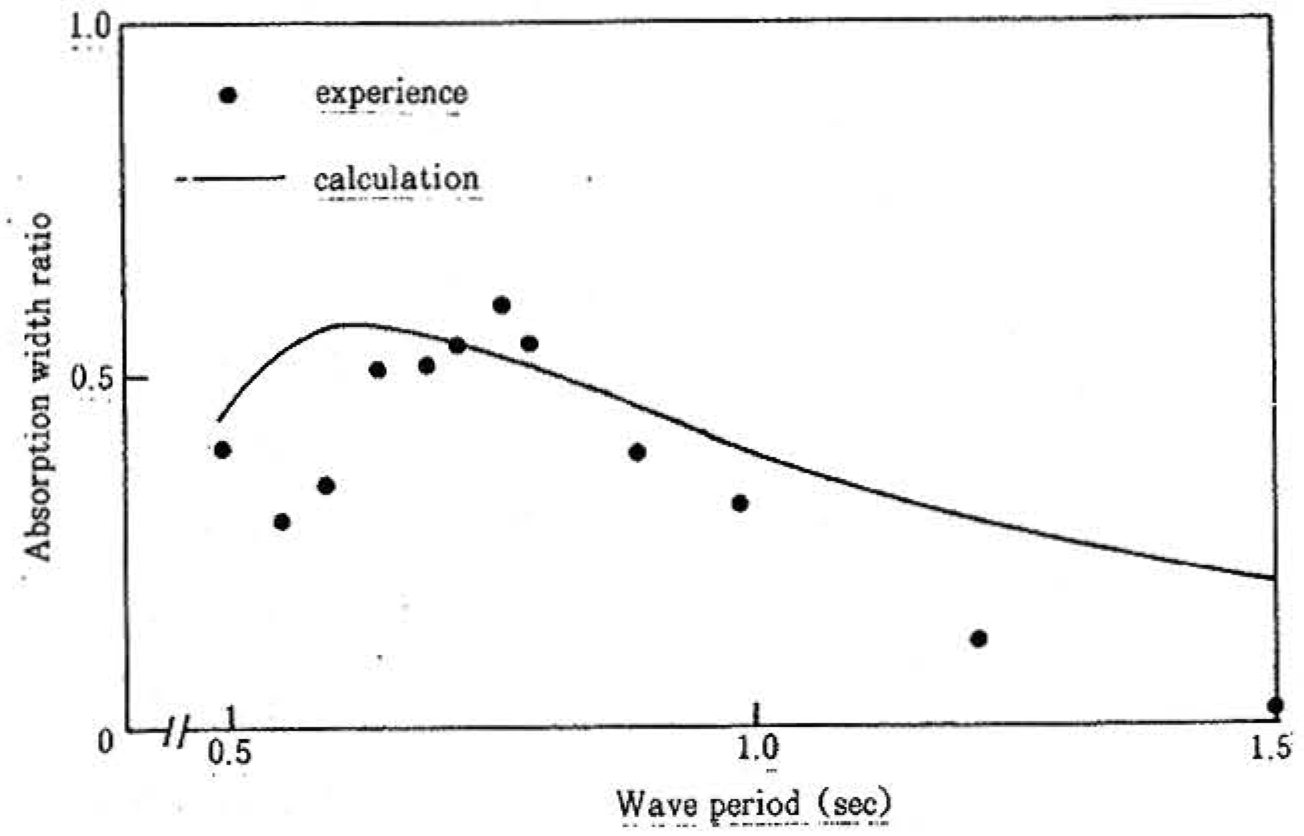



Fig. 6 Performance of wave energy absorption in regular waves by the Mighty Whale

Actually, as you can see, the performance of wave energy absorption, wave dissipation and mooring force are very convenient behavior for the wave power device. Because, the efficiency of wave energy absorption is high against the wide region of wave period, the ratio of transmitted wave height is less than 0.5 in the region of about 1.0sec in wave period for the 1／100 scale model, and the mooring force is very small, sometimes, it was minus value.

When the mooring force was minus, we could observe very special phenomenon. That is slow propulsion to the opposite direction of wave propagation. We guess that the reason of this phenomenon caused from the difference of pressure between the front part and the rear part of the Mighty Whale. And, this difference was caused by the wave energy absorption by the air chamber which is attached at the front part of the Mighty Whale. Still now, we did not make clear on it quantitatively. But, this event is so interesting for the floating structure that we are going to analyze later.

## 5 CONCEPTION OF UTILYZATION OF THE MIGHTY WHALE

Wave energy has two shortcoming from the view point of conventional utilyzation. One is the fluctuation, and the other one is the problem on the cost. However, fortunately, since it will be installed in ocean, so the wave power device has a opportunity to take advantage such chance. Because, there are a lot of demands to supply the energy for many purpose in the ocean. For example, there are fishery, marine amusement and sports, navigational aids and refreshment of the environment.

In order to solve the problems of the fluctuation of wave energy, several strage systems for energy are studied. Authors thought that the most convenient type to strage the energy is "Compressed Air Energy Strage (CAES)" in the ocean. In our conception, this system is considered with a compressed air tank on the sea bed, some air pipe lines to connect from the tank to land, and the wave power device which produce the compressed air, as shown in Fig. 7. The compressed air which is produced by the Mighty Whale and straged in the tank is send with clean sea water as a condition of mixed flow to the area to be refreshed. Consequently, this system perform the aeration and the exchange of sea water in enclosed coastal sea.

For design and quantitative discussion on this system, we need more precise information and surveyed data on the condition of pollution of

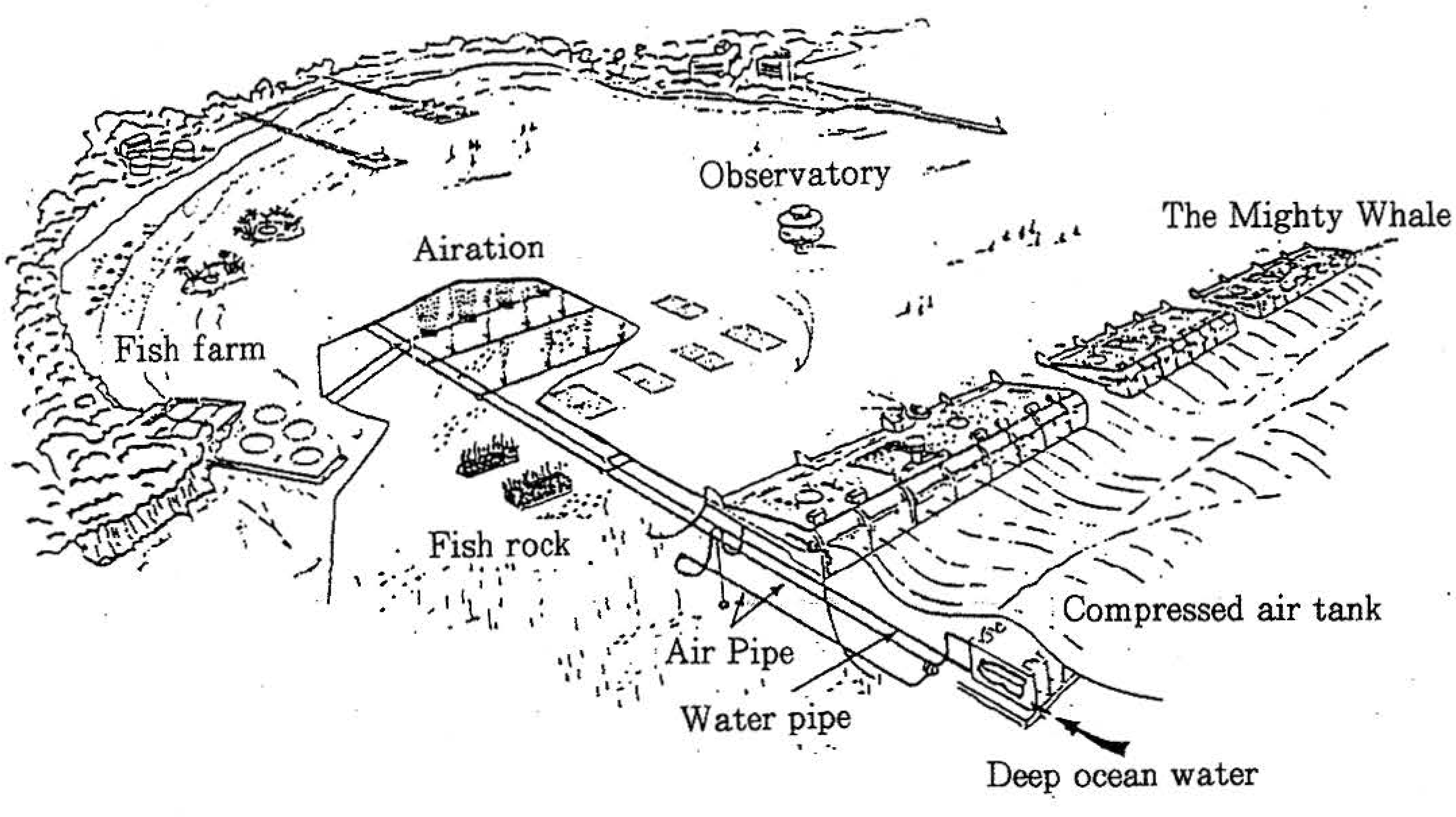



Fig. 7 A scheme of conception for utilization of the Mighty Whale for refreshment of marine environment

sea water, area and volume to be refreshed and wave condition at the site. In this paper, we only propose new conception to utilyze the wave power device. Because, that is the biggest obstruction and the most important item for the wave power device to reach the stage of practical use.

## 6 CONCLUSION

(1) The Mighty Whale is a floating terminator OWC type wave power device and has several superior behaviors. These are, the high efficiency of wave energy absorption, the high performance of dissipation of wave and very small mooring force.

(2) The high efficiency of wave energy absorption is caused by small responce of pitch and heave motion in waves. the high performance on wave height dissipation is caused by same reason. However, even under such condition, mooring force, that is drifting force is very small, and sometimes it becomes minus value.

(3) In spite of some shortcoming of the wave power device, the Mighty Whale has a good possibility for utilization in the ocean. That is the supply of air and clean sea water to enclosed coastal sea which has a problems on the polution. Furthermore, the Mighty Whale will be used for the marine leisure on it. That means the Mighty Whale is a multi purpose ocean structure.

## Reference

1 ) Ishii, S., Miyazaki, T., Masuda, Y., Kai, G. : "Reports and future plants for the KAIMEI project" , Proceedings of the 2nd International Symposium on Wave Energy Utilization, the Norwegian Institute of Technology (NTH), Norway, p.305-p.322, (1982)

2 ) International Energy Agency ; "Open Sea Trials" , Implementing Agreement for a Programme of Research and Development on Wave Power, Annex 2, Volume 4, (1987)

3 ) Hotta, H., Miyazaki, T., Washio, Y., Ishii, S.: "On the Performance of the Wave Power Device KAIMEI" Proceedings of the seventh international conference on offshore mechanics and arctic engineering (OMAE) , Volume 1, p.91-p.96, (1988)

4 ) Hotta, H., Washio, T., Ishii, S., Masuda, Y., Miyazaki, T., Kudo, K., : "The operational test on the shore fixed type wave power generator", Proceedings of the fifth international symposium of OMAE, volume 2, p.546-p.552, (1986)

5 ) Miyazaki, T., Hotta, H., Washio, Y., : "Design and Performance of the Mighty Whale Wave Energy Convertor" , World Renewable Energy Congress, U.K., Sept. (1990)

6 ) Hotta, H : "On the Behavior and Perform ance of the Floating Offshore Wave Power Device (FOWD) " , Proceedings of the Fourth Pacific Congress on Marine Science and Technology (PACON 90) , Volume 1, P.435-P.443, (1990)

7 ) Takahashi, S., Ojima, R., Suzumura, S : "Air Power of Pneumatictype Wave Power Extractors due to Irregular Wave Actions" , Report of the Port and Harbour Research Institute, Vol. 24, No. 1, (1985)

8 ) Miyajima, S., Masuda, K. : "Study on the Characteristics of a Barge Type Offshore Structure with an OWC Type Power Device" , Proceedings of 2nd symposium on Wave Energy Utilization in Japan, JAMSTEC, p.329-p.336, (1987)

(Received : 5 December 1991)

# 海域環境改良のための新型波力装置の利用について

堀田　平*2　宮崎　武晃*2　鷲尾　幸久*2

本報においては，主に以下の三つの項目について検討した結果を報告する。

まず，浮体式ターミネータ方式のOWC型波力装置の特徴と特性が述べられている。本方式装置は沖合に係留され，波エネルギーを他のエネルギーに効率良く変換するとともに，装置後方の海域を静穏化することができる機能を有している。

第二に，この方式の波力装置を応用するケースとして，筆者らは浮体式波力装置の新たな概念を導いた。それがマイティホエールと称される波力装置であり，これの有するいくつかの機能である。

第三に，マイティホエールによって波エネルギーを利用して作り出された圧縮空気の利用について，筆者らは海域環境の改良に用いることを提案している。なぜならば，波エネルギーはクリーンで再生可能なエネルギー源であるからである。

キーワード：海洋エネルギー，波エネルギー，波力装置，海域環境

＊2　海域開発研究部