파력 발전기에 미치는 유체력의 제어에 관한 연구

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A Study on the Control of Hydrodynamic Forces for Wave Energy Conversion Device Operating in Constantly Varying Ocean Conditions

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CONTENTS

요 약

부유식 진동수주형 파력발전기는 불규칙한 해상 상태에서의 작동으로 인하여 흡수효율의 저하를 필수적으로 수반한다.

본 논문에서는 입사파의 에너지를 적절히 흡수할 수 있는 파력발전기를 초기설계하여 모델로 이용하였으며, 이 모델의 유체력 추정에는 3차원 특이점 분포법을 사용하였다. 그리고, 가변구조 시스템으로 알려진 슬라이딩 모드기법을 이용하여 파의 상태 변화에 따른 파력발전기의 자세와 위치를 제어함으로써 흡수파력의 효율을 증대시킬 수 있는 시스템을 제안하고 있다.

Key Words : Sliding Mode Method, Variable Structure System, Feedback, Water Column.

Nomenclature

M_A : Mean Values
A : Added Mass
C : Design Coefficient
D : Damping Coefficient
H : Wave Height
F : Wave Exciting Force
L : Length of Model

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M : Mass of Wave Energy Conversion Device
R : Restoring Coefficient
S(t) : Switching Plance
u : Input Torque of Control
X : Position of Surge Direction
X_d : Design Position of Surge Direction
Y : Position of Sway Direction
Y_d : Design Position of Sway Direction
θ : Angular Position of Yaw Direction
θ_d : Design Angular Position of Yaw Direction
ξ : Heave Motion Amplitude of Device
λ : Wave Length
(Additional Subscript)
i : X, Y, θ
ξ : X, Y, θ
· : Time Derivative

Abstract

Due to the constantly varying sea－states with which any wave energy conversion device must contend in order to extract energy efficiently, the ability to control the device's position relative to the incident waves is critical in achieving the creation fo a truly functional and economical wave energy device.

In this paper, the authors will propose methodology based on the theory of a variable structure system to utilize a three dimensional source distribution as a model to estimate anticipated surge, sway and yaw of a wave energy conversion device relative to varying angles and characteristics of incident waves and therefrom derive a feedback to a sliding mode controller which would reposition the device so as to maximize its ability to extract energy from waves in constantly varying ocean conditions.

1. Introduction

Previous attempt to efficiently extract energy from ocean waves did not achieve the desired results due to the high degree of structural complexity which must be incorporated into any wave energy conversion device attempting to extract energy from the non－linear hydrodynamic phenomena that characterize ocean wave. Ocean waves may come from any direction of incidence and have different characteristics of wave height, length, etc. The combination of these two sources of complexity make it extremely difficult to estimate or promote extracted wave power, as previously demonstrated both theoretically and experimentally(Kim and Park, 1989), (Kudo, 1984).

Therefore, a three dimensional source distribution method is used to estimate the hydrodynamic forces on a wave energy conversion device and to calculate the hydrodynamic forces according to the variations in length and direction of incident waves(Kim and Park, 1989), (Kim and Park and Kim, 1988). And the authors belive it is possible to control the position of a wave energy conversion device by using a "water column" model's three dimensional source distribution. The varlances in the model water column's height are then used to calculate the hydrodynamic forces acting upon the wave conversion devices. The controller capable of effecting an appropriate physical repositioning of the device commensulate with varying ocean wave conditions as modeled by the water column (See Fig.1).

At present, dynamic position control systems require the forecasting of an exact wave exciting force and their resultant distubance. This impractical prerequisite makes them far too costly to implement (Harris and Billings, 1979), (Kang, 1990), (Yeung and Chen, 1988). In order to avoid this pitfall, a control algorithm based on the theory of variable structure systems has been developed. In this case, the variable structure system has been designed in such a way that all trajectories in the state space are directed toward some swithching plane (Kang, 1990), (Yeung and Chen, 1988).

In this way, the previously described sliding mode controller is able to control the position and direction of the wave energy conversion device's surge, sway and yaw.

2. Hydrodynamic Forces

Due to the structural characteristic of wave ehergy conversion devices, the three dimensional source distribution method is a paticularly useful way to calculate the hydrodynamic forces acting upon them.

This is done by simulation the reaction of three dimensional source water column model to varying wave conditions such as those to which a conversion device is exposed. The logical next step, of course, would be to utilize a water column on the device itself to calculate and produce feedback to the device's controller.

The model proposed in this paper has a design wave height of 2m and design wave length of 80 m. This floating room is of the proper dimension to constrain the amplitude of heave, roll and pitch (Kim and Park, 1989). A computer simulation for heave motion is presented in Fig.3. It demonstrates that heave motion amplitude varies greatly with changes to the angle of incidence of an on−coming wave. And, motion amplitudes of roll ad pitch are substantial indicators of incident wave direction.

A comparision of Fig.3 with Fig.4 through 6 confirms that motion amplitude is inversely propotinal to the amplitude of the fluid in our water column model.

Control using Sliding Mode Method by variable Structure System Theory.

Consider the second order dynamic equation for surge, sway and yaw direction in device.

$$M_A\ddot{q}+D\dot{q}+Rq=F+u \qquad (1)$$

$$q = \begin{bmatrix} X \\ Y \\ \theta \end{bmatrix}$$

$$M_A = \begin{bmatrix} M+Ax & 0 & 0 \\ 0 & M+Ay & 0 \\ 0 & 0 & M+A_Q \end{bmatrix}$$

$$D = \begin{bmatrix} Dx & 0 & 0 \\ 0 & Dy & 0 \\ 0 & 0 & D_Q \end{bmatrix}$$

$$R = \begin{bmatrix} Rx & 0 & 0 \\ 0 & Ry & 0 \\ 0 & 0 & R_Q \end{bmatrix}$$

$$F = \begin{bmatrix} Fx \\ Fy \\ F_Q \end{bmatrix} \qquad u = \begin{bmatrix} ux \\ uy \\ u_Q \end{bmatrix}$$

Let q_d represent the desired position and chose the switching planes $S^T = [Sx, Sy, S_Q] = O^T$

$$S = C\,(q - q_d) + \dot{q} \qquad (2)$$

Where, $C = \mathrm{diag}[Cx, Cy, C_Q]$

$Cx, Cy, C_Q > 0$

The aim of the control is to force the motion of the system to be along the intersection of the switching planes $S = 0$. Differentiating (2) with respect to time gives.

$$\dot{S} = C\dot{q} + \ddot{q} \qquad (3)$$

Intersecting (1)

$$M_A(\dot{S}-C\dot{q})+D\dot{q}+Rq=F+u \qquad (4)$$

$$M_A\dot{S}=(M_AC-D)\,\dot{q}-Rq+F+u \qquad (5)$$

We now derive a reaching condition for the switching planes using the stability theorem of Lyapunov (Landau, 1979). Assume the form of $M_A\dot{S}$ to be

$$M_A\dot{S} = \begin{bmatrix} -P_x,\ \mathrm{sgn}\ (S_x) \\ -P_y,\ \mathrm{sgn}\ (S_y) \\ -P_Q,\ \mathrm{sgn}\ (S_Q) \end{bmatrix}$$

$$= -\{P_i\ \mathrm{sgn}\ (S_i)\ /\ S_i\}\ S \qquad (6)$$

where, P_x, P_y, $P_Q > 0$

$$\mathrm{sgn}(S) = \begin{cases} 1 & S > 0 \\ -1 & S < 0 \\ 0 & S = 0 \end{cases}$$

For using asymptotically stable Lyapunov Function, define Lyapunov Function to be

$$V\ (S,\ \dot{S}) = S^T M_A S \qquad (7)$$

Since M_A is positive definite, $V\ (S,\ \dot{S})$ is a positive semi-definite function. Moreover $V\ (S,\ \dot{S})$ vanish only for $S = 0$. Differentiating with respect to time.

$$\dot{V}\ (S,\ \dot{S}) = \dot{S}^T M_A S + S^T \dot{M}_A S + S^T M_A \dot{S}$$
$$= (M_A\dot{S})^T S + S^T \dot{M}_A S + S^T M_A \dot{S} \qquad (8)$$

Intersecting (6) in the above equation

$$\dot{V}(S,\ \dot{S}) = -2\mathrm{diag}[P_i\ \mathrm{sgn}(S_i)\ /\ S_i]\ SS^T$$
$$+ \dot{M}_A SS^T \qquad (9)$$

For using asymptotic stable Lyapunov function in sliding mode, diag $[P_i\ \mathrm{sgn}\ (S_i)\ /\ S_i] - \dot{M}_A\ /\ 2$ Should have done the positive definite matrix. so that,

$$P_i\ \mathrm{sgn}\ (S_i)\ /\ S_i > \sum_j \dot{M}_A\ /\ 2 \qquad (10)$$

From the coorelation between (5) and (6)

$$(M_A C - D)\ \dot{q} - Rq + F + u$$

$$= \begin{bmatrix} -P_x\ \mathrm{sgn}\ (S_x) \\ -P_y\ \mathrm{sgn}\ (S_y) \\ -P_Q\ \mathrm{sgn}\ (S_Q) \end{bmatrix} \qquad (11)$$

Let $M_A C - D = (M_A C - D)^\circ + \delta(M_A C - D)$

$R = R^\circ + \delta R$

Where, M_A°. R° : mean values

Assume the following bounds for $M_A C - D$, R, F and M

$$M_A C - D = (M_A C - D)^\circ + \delta(M_A C - D)$$
$$< (M_A C - D)^\circ + \alpha(M_A C - D)$$
$$R = R^\circ + \delta R < R^\circ + \alpha R$$
$$F < \alpha F$$
$$M_A < \alpha M_A \qquad (12)$$

Intersecting the above relation equation in (5)

$$M_A\dot{S} = (M_A C - D)^\circ \dot{q} + \delta(M_A C - D)\dot{q}$$
$$- Rq + F + u$$
$$= (M_A C - D)^\circ \dot{q} - R^\circ q - u'$$
$$+ \delta(M_A C - D)\dot{q} - \delta R q$$
$$+ F + u' + u \qquad (13)$$

Let the control law

$$u = -(M_A C - D)^\circ \dot{q} + R^\circ q + u' \qquad (14)$$

From (6) and (12)

$$\delta(M_A C - D)\dot{q} - \delta R q + F + u'$$

$$= \begin{bmatrix} -P_x\ \mathrm{sgn}\ (S_x) \\ -P_y\ \mathrm{sgn}\ (S_y) \\ -P_Q\ \mathrm{sgn}\ (S_Q) \end{bmatrix} \qquad (15)$$

combining (10) and (15)

$$\mathrm{sgn}(S_i)\ \{\sum_j \delta(M_A C - D)\dot{q} - \delta R q + F + u'\}$$
$$< -|S_i| \sum_j \dot{M}_A / 2 \qquad (16)$$

Using (12), it is arranged (15) to be

$$u' = -\mathrm{sgn}(Si)\ \{\sum_j \alpha(M_A C - D)\dot{q} + \alpha Rq - \alpha F\} - Si \sum_j M_A / 2 \qquad (17)$$

Intersecting the above equation (17) in control law (14), desired control law.

$$u = -(M_A C - D)\circ\dot{q} + R\circ q - Si\sum_j M_A / 2 - \mathrm{sgn}(Si)\ \{\sum_j \alpha(M_A C - D)\dot{q} + \alpha R\dot{q} - \alpha F\} \qquad (18)$$

The actual control u consists of a low-frequency (average) component and a high-frequency(chatter) component. sgn(Si) in above equation is discontinuous sign function. So, this function is replaced by a proper continuous function as follows (Hashimoto, Maruyama and Harashima 1987).

$$\mathrm{sgn}\ (Si) \quad \frac{Si}{|Si| + \beta_i}$$

β_i : Positive Constant

finally control law is

$$u = -(M_A C - D)\circ\dot{q} + R\circ q - Si\sum_j \dot{M}_A / 2 - Si / (|Si| + \beta_1) \{\sum_j \alpha(M_A C - D)\dot{q} + \alpha Rq - \alpha F\} \qquad (19)$$

3. Simulation for Control

Simulation of the actual use of such a control system upon a wave energy conversion device is the next step. To do this, we input the design datum parameters of the device, namely, mass, added mass coefficient, damping coefficient, restorring coefficient and wave exciting force on each direction surge, sway and yaw. Restoring coefficient is calculated as zero in consideration of cable line, drift force, etc. A coefficient is considered in equation (12), namely, the values of the boundary upper limits, already shown in the figures.

In a real situation where in the system parameters are not exact values, this method has the advantage that it is able to control with the values of the boundary upper limit. The design position is then decided as a consideration of Lloyd's Register for platform support.

Figs. 7,10,13,16 and 19, we can see the variation of position to time and the stable position when reached at design position.

Figs. 8,11,14,17 and 20, show the variation of the input torque to time. It is shown that the input is stable when reached at design position inspite of introducing random number(wave exciting force disturbance) within the values of upper limit.

Figs. 9,12,18 and 21, show the correlation between position (X&Y) and velocity ($\dot{X}$&$\dot{Y}$), from which it is found that the velocity very much decreases in the sliding lines. This also confirms the stable of positioning control because the velocity does not vary at the design position.

The correlation between position (θ) and angular velocity ($\dot{\theta}$) is shown in Fig.15 and there is a small fluctuation in angular velocity at the design position.

We are therefore able to determine that the design position (X_d, Y_d, θ_d), design constant (C_x, C_y, C_Q) and values of the boundary upper limit of wave exciting force directly influence the results of simulation and can demonstrate this by running the simulation using different values for the variables.

Somewhat, even though it is added random values(less than boundary upper limits) to wave exciting force in the course of simulation, it is confirmed that it is able to control the position.

4. Conclusions

A variation of position of the wave energy device and effects of its position relative to the incident wave may be determined by utilizing the results obtained through the three dimensional source distribution of hydrodynamic forces in the water column of the device.

The variable structure system informed sliding mode control is useful as a control method for structures in irregular regions such as the ocean. Simulation of such a control upon a model device in accordance with the variable structure system theory produced a satisfactory result.

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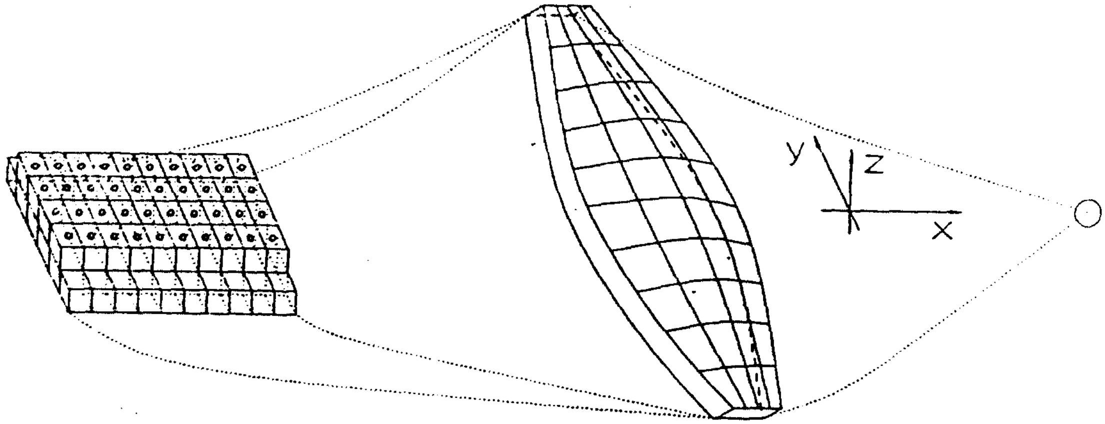

Fig. 1 Coordinate and Wave Energy Conversion System

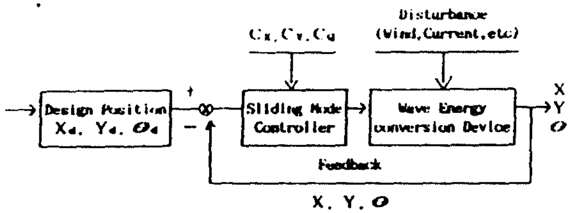

Fig. 2 Block Diagram of Control System

Table 1. Dimension of Model

Model		Model		Model	
Length	80.0 M	V.C.G.	4.0 H	Water Depth	∞
Breath	36.0 M	L.C.G.	0.0 H	Wave Height	1.0 M
Depth	10.0 M	T.C.G.	0.0 H	Water Area A_w	74.625 M^2
Draft	4.0 M				

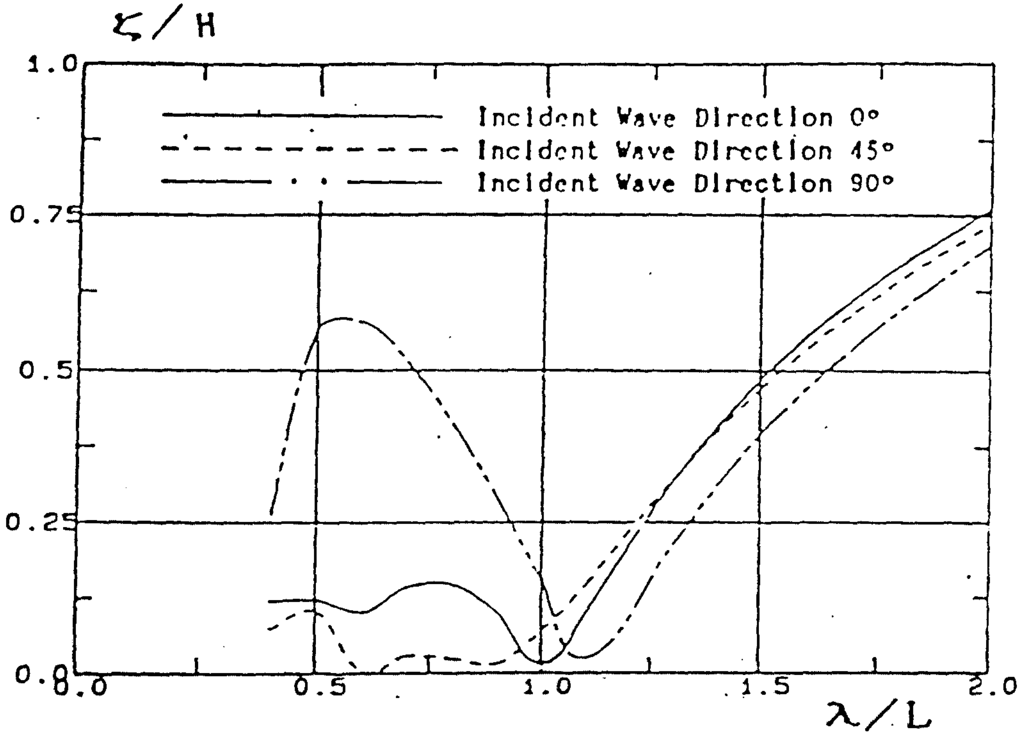

Fig. 3 Heave Motion Amplitude for Model (Even Condition)

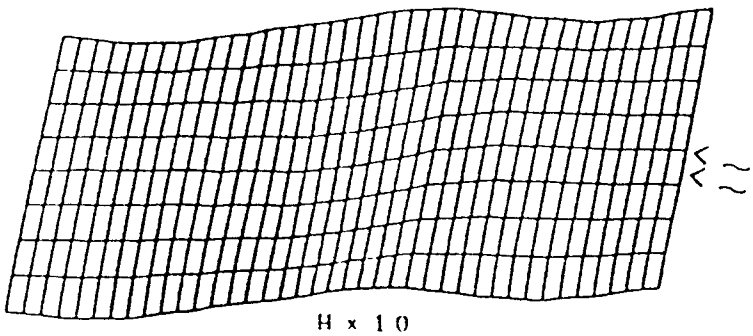

Fig. 4 Distribution of a Fluid in Water Column (λ/L=0.7 Incident wave Direction=0°)

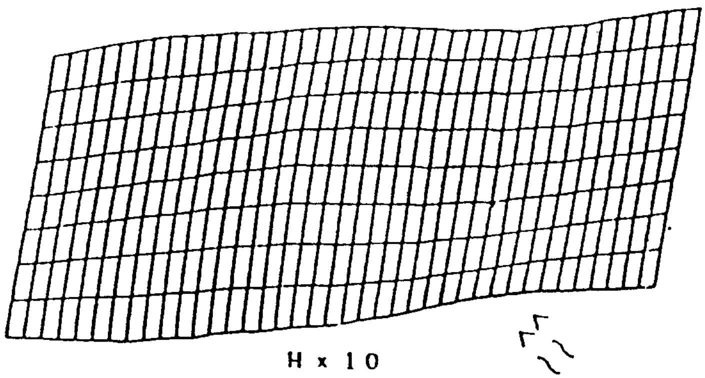

Fig. 5 Distribution of a Fluid in Water Column (λ/L=0.7 Incident wave Direction=45°)

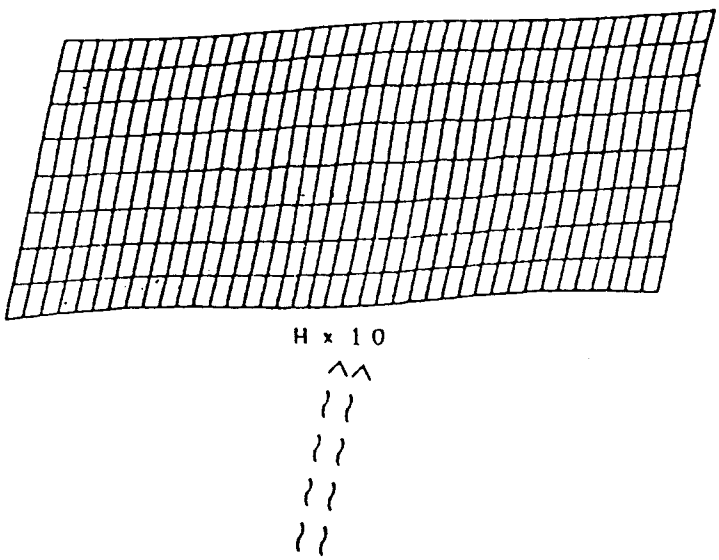

Fig. 6 Distribution of a Fluid in Water Column (λ/L=0.7 Incident wave Direction=90°)

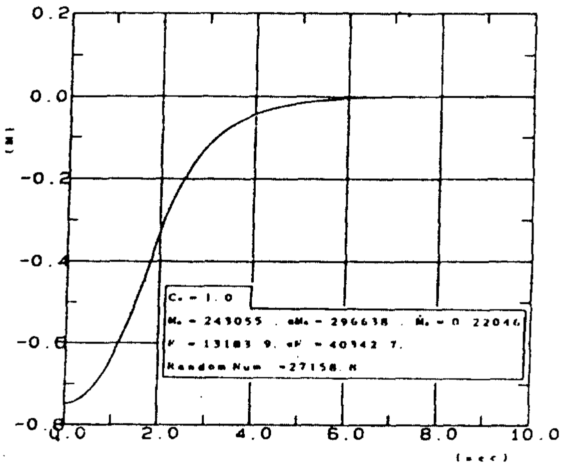

Fig. 7 Variation of Surge Position according to Time
(λ/L=0.7, Incident wave Direction=0°)

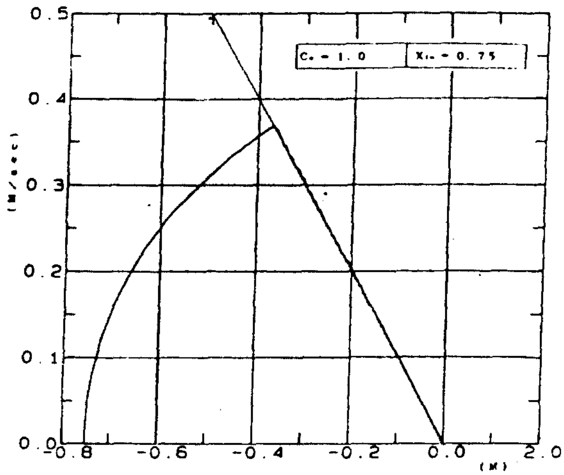

Fig. 9 Variation of Velocity in Sliding Plane according to Surge Position
(λ/L=0.7, Incident wave Direction=0°)

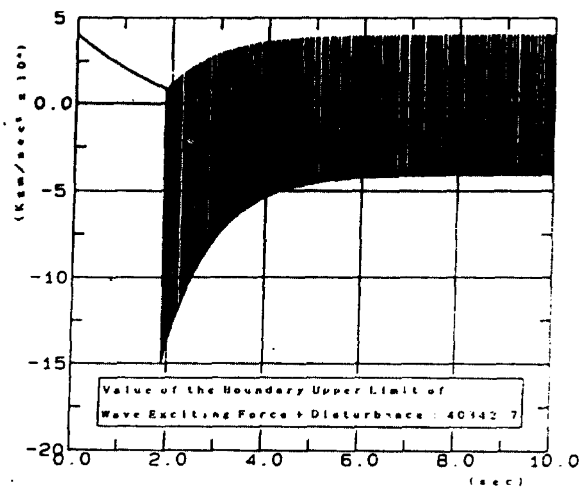

Fig. 8 Variation of Input Torque according to Time in Surge
(λ/L=0.7, Incident wave Direction=0°)

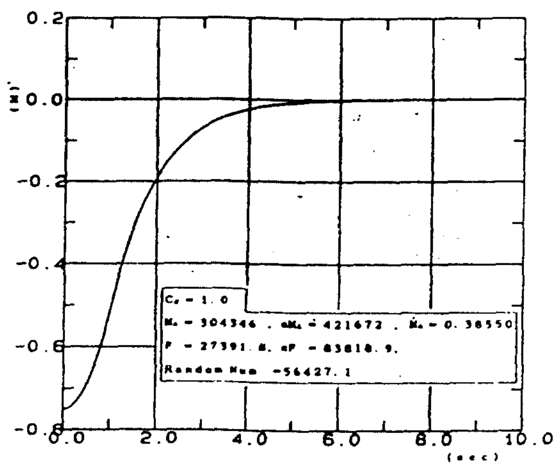

Fig. 10 Variation of Sway Position According to Time
(λ/L=0.7, Incident wave Direction=90°)

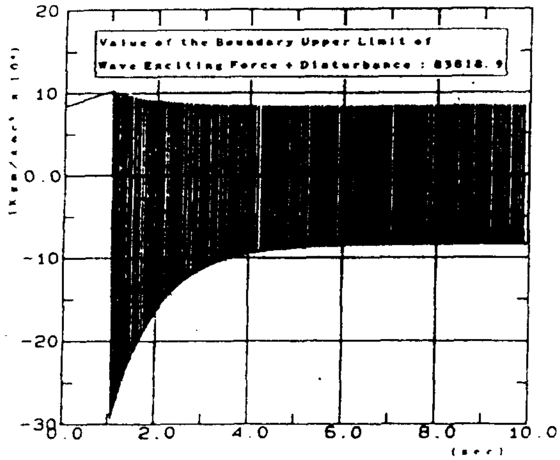

Fig. 11 Variation of Input Torque
according to Time in Sway
(λ/L=0.7, Incident wave Direction=90°)

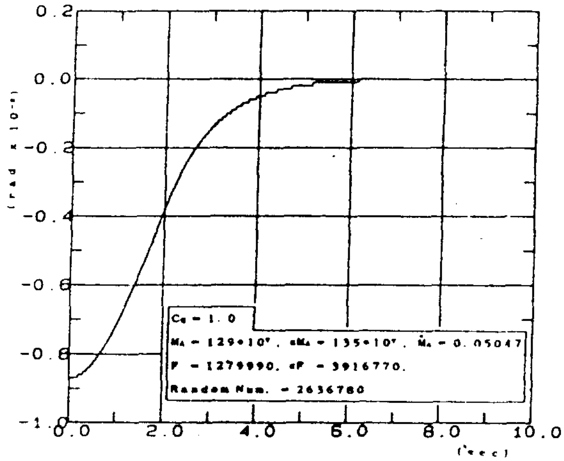

Fig. 13 Variation of Yaw Position according to
Time
(λ/L=0.7, Incident wave Direction=45°)

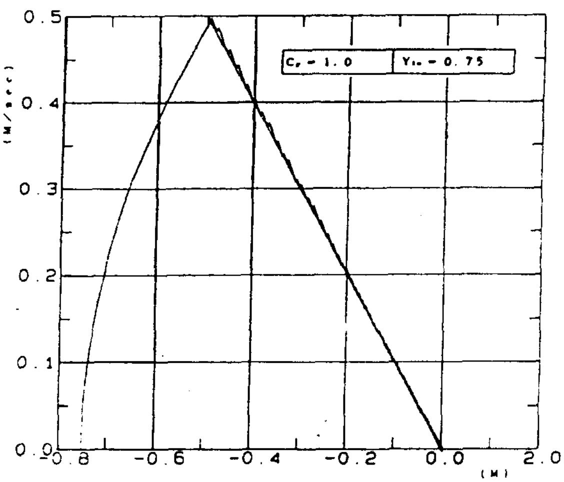

Fig. 12 Variation of Velocity in Sliding Plane
according to Sway Position
(λ/L=0.7, Incident wave Direction=90°)

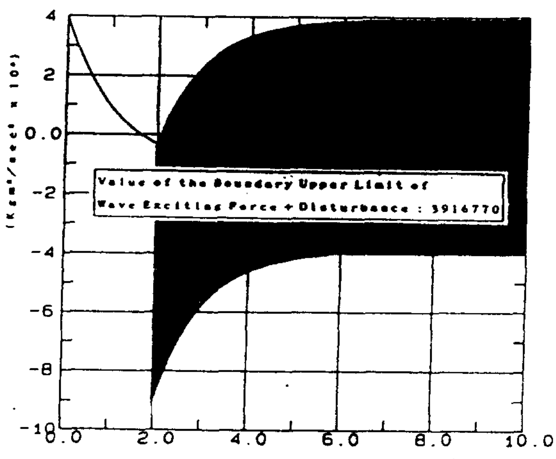

Fig. 14 Variation of Input Torque
according to Time in Yaw
(λ/L=0.7, Incident wave Direction=45°)

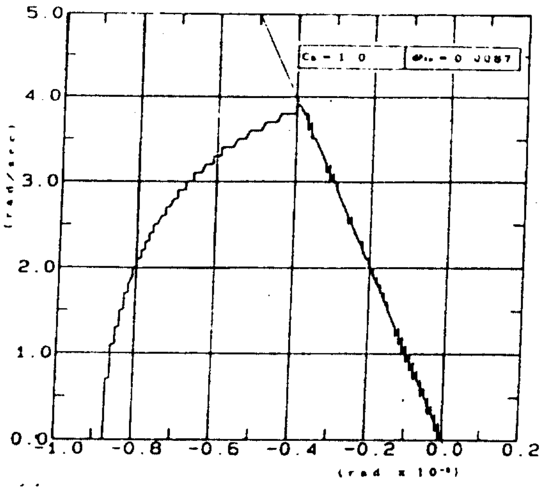

Fig. 15 Variation of Velocity in Sliding Plane according to Yaw Position
(λ/L=0.7, Incident wave Direction=45°)

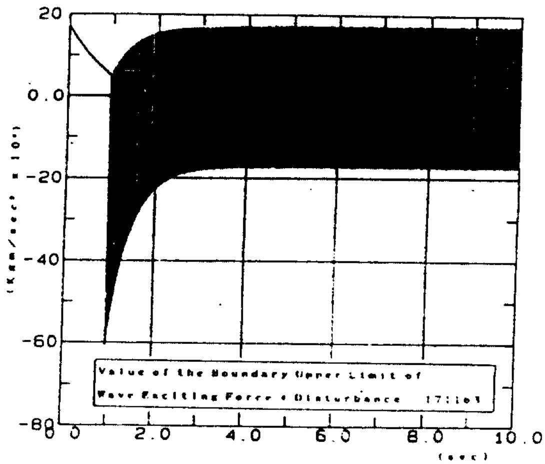

Fig. 17 Variation of Input Torque according to Time in Surge
(λ/L=1.0, Incident wave Direction=0°)

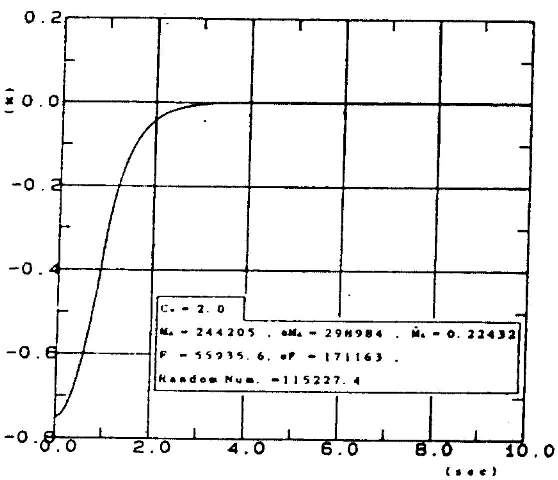

Fig. 16 Variation of Surge Position according to Time
(λ/L=1.0, Incident wave Direction=0°)

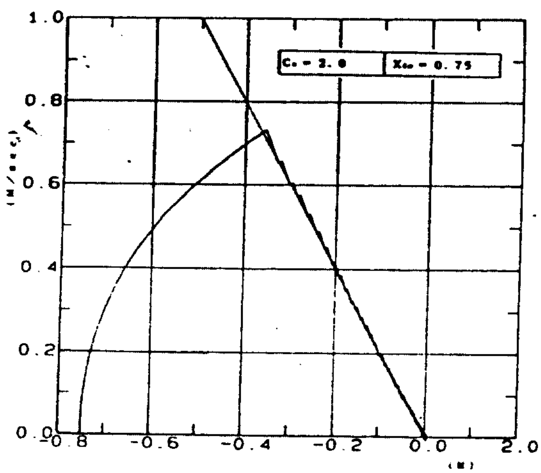

Fig. 18 Variation of Velocity in Sliding Plane according to Surge Position
(λ/L=1.0, Incident wave Direction=0°)

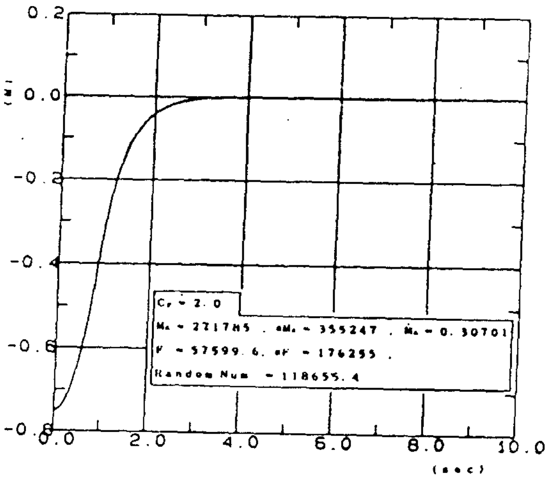

Fig. 19 Variation of Sway Position according to Time
(λ/L=1.3, Incident wave Direction=90°)

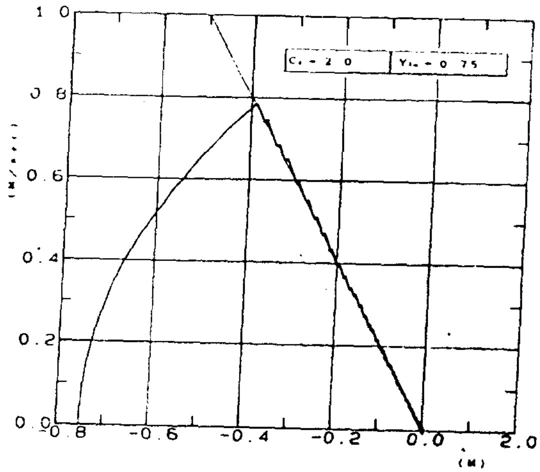

Fig. 21 Variation of Velocity in Sliding Plane according to Sway Position
(λ/L=1.3, Incident wave Direction=90°)

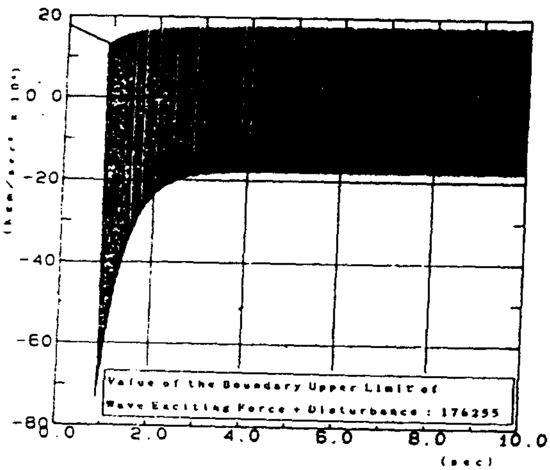

Fig. 20 Variation of Input Torque according to Time in Sway
(λ/L=1.3, Incident wave Direction=90°)