Bulletins of Research Institute of Marine Science and Technology
Korea Maritime University, Vol. 4, pp. 127 – 139, December 1995.

INTERNATIONAL SYMPOSIUM
ON VTS & IBS '95
NOVEMBER 2-3, 1995

A Study on the Prediction of Propulsive Energy Loss Related to Automatic Steering of Ships

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Abstract

When an automatic course-keeping is introduced, as is quite popular in modern navigation, the closed-loop steering system consists of autopilot device, power unit(or telemotor unit), steering gear, ship dynamics, and magnetic or gyro compass. We derive the mathematical model of each element of the automatic steering system. We provide a method of theoretical analysis on propulsive energy loss related to automatic steering of ships in the open seas, taking account of the on-off mechanism of power unit. Also we paid attention to dead band mechanism of autopilot device, which is normally called weather adjustment. Next we make numerical calculation of the effects of autopilot control constants on the propulsive energy loss for two kinds of ship, a fishing boat and an ore carrier. Realistic sea and wind disturbances are employed in the calculation.

1. Introduction

Generally researches on ship operation can be divided into two fields. One is in relation to safety problem mainly in harbour area or coastal waters. The other is in relation to economy problem mainly in the open seas. In the former case, improvement of manoeuvrability of every ship or exact information on her manoeuvrability and environment will insure the safety of ship operation to some extent. In the latter case, we come to be interested in propulsive energy loss related to automatic steering from the standpoint of economy.

Nomoto[1] pointed out that the marine autopilots entailed unfavorable yawing with prolonged periodicity, which caused an increase in propulsive energy. Later

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then Koyama[2], Bech[3], Hasegawa[4], Tsubokawa[5] et al. suggested the various methods to evaluate or to analyze automatic steering system. They forecasted propulsive energy losses of between 2% and 20% related to automatic steering. It is desired that the control constants of autopilot device should be decided or to be adjusted to minimize the loss of propulsive energy from an economic point of view. The irregular disturbances to ship dynamics and a few non-linear mechanisms installed inevitably or artificially are considered very important in evaluating or analyzing automatic steering system.

We provided the realization method of irregular disturbances to ship dynamics in automatic steering system in Reference 6. We also derived the performance index of automatic steering system from the concept of propulsive energy loss in Reference 7. In this paper, we provide a method of theoretical analysis on propulsive energy loss related to automatic steering of ships in the open seas, taking account of a few non-linear mechanisms. Next we make numerical calculation of the effects of autopilot control constants on the propulsive energy loss for two kinds of ship, a fishing boat and an ore carrier. Realistic sea and wind disturbances are employed in the calculation according to Reference 6.

2. Mathematical model of automatic steering system

Fig. 1 shows the block diagram of the general type of automatic steering system available for modern ships. The dynamics or input/output characteristics of each element of the composition of automatic steering system, is well modelled mathematically as follows.

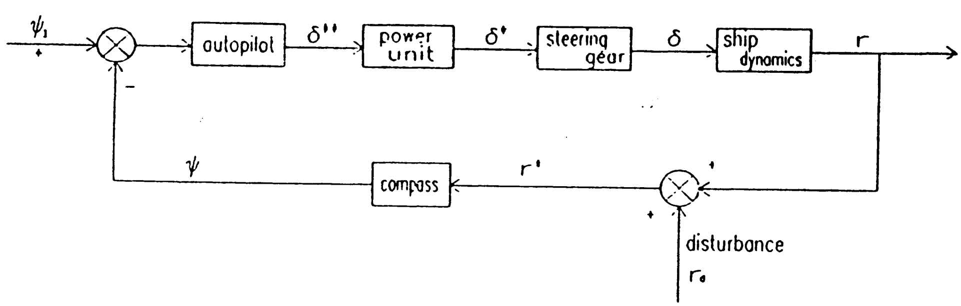


Fig. 1 Block diagram of automatic steering system

Ship dynamics

According to Nomoto[1], the equation of ship dynamics during course-keeping can be written as follows.

$$T_1' T_2' \left(\frac{L}{V}\right)^2 \ddot{r} + (T_1' + T_2')\left(\frac{L}{V}\right) \dot{r} + r = K' \left(\frac{V}{L}\right)\delta + K' T_3' \dot{\delta} \qquad (1)$$

where δ denotes rudder angle, r the yaw rate due to rudder deflection, V ship speed, L ship length, and T_1', T_2', T_3' and K' manoeuvring indices. A dot over the parameters of ship motion represents time derivative.

Compass

The mathematical model of magnetic or gyro compass is self-evident as follows.

$$\psi = \int_0^t r^* dt \ , \quad r^* = r + r_d \tag{2}$$

where t denotes time elapsed, r_d the yaw rate due to wave/wind disturbances, and ψ actual heading angle.

Autopilot

As autopilot characteristics, we adopt the PROPORTIONAL-DERIVATIVE (PD) controller plus low-pass filter with weather adjustment[8],[9]. A low-pass filter is added to the controller in order to counter the excessive rudder movement due to the derivative term. A weather adjustment is necessary for less wear and tear of the steering equipment. Eq.(3), below, represents the dynamics of adopted autopilot.

$$\delta' + T_{cr}\,\dot{\delta}' = -(\psi - \psi_I) - T_D r^*$$

$$\delta^{**} = \begin{cases} K_P(\delta' - b) & : \quad (\delta' > b) \\ K_P(\delta' + b) & : \quad (\delta' < -b) \\ 0 & : \quad (|\delta'| \leqq b) \end{cases} \tag{3}$$

where δ' denotes input signal to weather adjustment, δ^{**} the electrical signal in terms of commanded rudder angle, ψ_I predetermined, desired heading angle, $2b$ dead band width of weather adjustment, K_P rudder gain, T_{cr} time constant of low-pass filter, and T_D time constant of derivative or yaw rate control. Furthermore we adopt the following relation.

$$T_D = K_{cr}\,T_{cr} \tag{4}$$

where K_{cr} denotes counter rudder gain. It is desired that T_D should be larger value than T_{cr} from the viewpoint of filter characteristics.

Power unit

The steering mechanism in most ships is electro-hydraulic system, which consists of power unit(or telemotor unit) and steering gear. The power unit is a kind of hydraulic pump to actuate hydraulic rams of steering gear by converting the electrical signal from autopilot into the mechanical displacement corresponding to commanded rudder angle. We should remember that the non-liner, on-off mechanism has been installed in the solenoid valves in the power unit in order to exclude hunting phenomenon. The dynamics of power unit is modelled as follows[5].

$$\begin{aligned} \delta^* &= \delta_0^* & &: \quad (|\delta^{**} - \delta^*| \leqq 2\delta_b) \\ \delta^* &= \delta_0^* + \mathrm{sign}(\delta^{**} - \delta^*) \int_0^t \dot{\delta}^* dt & &: \quad (|\delta^{**} - \delta^*| > 2\delta_b) \end{aligned} \tag{5}$$

where δ^{**} denotes the electrical signal from autopilot in terms of commanded rudder angle, δ^* the mechanical displacement to steering gear in terms of commanded rudder angle, δ_0^* the initial value of δ^*, $\dot{\delta}^*$ the flow-rate of hydraulic pump in terms of rudder speed, and $2\delta_b$ pausing band width of on-off mechanism of solenoid valves in term of rudder angle.

Steering gear

Dynamics of a steering gear is well modelled by the following equation[10].

$$\begin{aligned} T_E \dot{\delta} + \delta &= \delta^* & &: \quad (|\dot{\delta}| \leq |\dot{\delta}_{max}|) \\ \dot{\delta} &= \text{sign}(\delta^* - \delta) |\dot{\delta}_{max}| & &: \quad (|\dot{\delta}| > |\dot{\delta}_{max}|) \end{aligned} \qquad (6)$$

where T_E denotes time constant, $\dot{\delta}_{max}$ maximum rudder speed. Normally the regulation requires to take 28 sec for rudder deflection of 65 deg. So T_E is around 2.5 sec, and the average pump capacity of steering gear provides $\dot{\delta}_{max}$ as around 3.0 deg/sec.

We can obtain the transfer function of each element of the composition of automatic steering system by Laplace transformations of eqs.(1), (2), (3), (5) and (6). Fig. 2 shows the block diagram of transfer functions of the closed-loop, automatic steering system which contains a few non-linear mechanisms. In this figure s denotes Laplace operator.

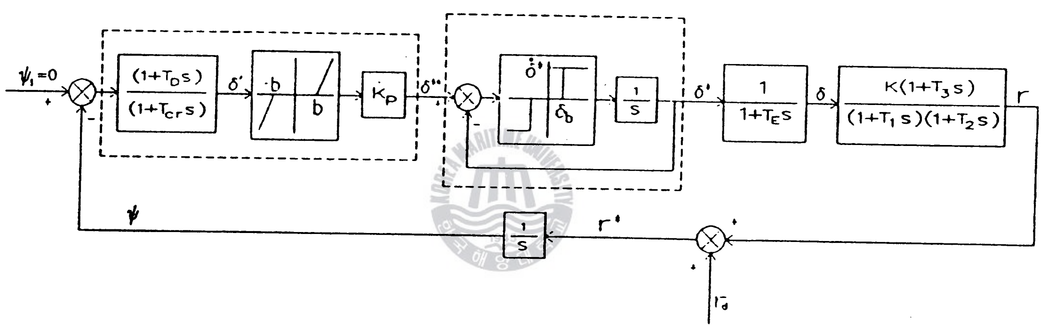


Fig. 2 Transfer functions of automatic steering system

3. Propulsive energy loss — performance index

If the hull design, engine characteristics and steering equipment are assumed to be fixed, the linear or non-linear control constants of autopilot device are desirable to be decided from an economic point of view. We can take fuel consumption as economic measurement. Fuel consumption is closely related to the propulsive energy which is essentially affected by the resistance on the ship. Propulsive energy loss due to yawing motion in the open seas compared with straight motion in calm waters, can increase the consumption of fuel.

We take performance index(or energy saving index or cost function) as the means of evaluating propulsive energy loss related to automatic steering of ships. We can define performance index J as follows[4].

$$J = \frac{E - E_o}{E_o} \qquad (7)$$

where E_o denotes propulsive energy required for straight sailing without any yawing from one port to the other, and E propulsive energy required for the actual voyage with steering from the same port to the other same port. So $(E - E_o)$ denotes propulsive energy loss related to automatic steering of ships. We have already proposed the expression of performance index[7] as follows, which have been based on eq.(7).

$$J = \frac{1}{2}\overline{\psi^2} + \frac{a'_{rr}}{a'_{VV}}\left(\frac{L}{V}\right)^2\overline{r'^2} + \frac{a'_{\delta\delta}}{a'_{VV}}\overline{\delta^2} \tag{8}$$

where $\overline{\psi^2}$, $\overline{r'^2}$ and $\overline{\delta^2}$ represent mean square values of ψ, r' and δ respectively, and a'_{VV}, a'_{rr} and $a'_{\delta\delta}$ hydrodynamic coefficients of surge equation, which have been defined in Reference 6 in detail.

There can be two kinds of calculation method on the performance index[7]. One is frequency response analysis, and the other simulation technique. The former cannot be applicable to non-linear system. So we should apply the simulation technique to calculation of J. Simulation technique is to solve directly the differential equations (1), (2), (3), (5) and (6) simultaneously using step-by-step integral approximation under given condition of realistic wave and wind disturbances. And then we can calculate mean square values of state variables of ship motion as follows.

$$\begin{aligned} \overline{\psi^2} &= \frac{1}{T_H}\int_0^{T_H}\psi^2\,dt \\ \overline{r^2} &= \frac{1}{T_H}\int_0^{T_H} r^2\,dt \\ \overline{\delta^2} &= \frac{1}{T_H}\int_0^{T_H}\delta^2\,dt \end{aligned} \tag{9}$$

where T_H denotes total time length for analysis.

4. Numerical calculation and discussion

4.1 Ships' particulars and steering characteristics

Two kinds of ship are chosen for present calculation of propulsive energy loss related to automatic steering in the open seas. One is ore carrier, and the other small fishing boat. Their principal particulars are shown in Table 1, and body plans and hull end profiles are presented in Figs. 3 ~4. The hydrodynamic coefficients, manoeuvring indices, and characteristics of steering sear and power unit are listed in Table 2 [6].

Table 1 Principal particulars of ships

items		ore carrier	fishing boat
HULL			
Length B.P.	L (m)	247.0	27.90
Breadth	B (m)	40.6	6.30
Mean draft	d (m)	16.0	2.25
Trim	τ (m)	0.0	0.0
Block coefficient	C_B	0.8243	0.6868
Midship section coefficient	C_M	0.9975	0.9695
Rudder			
Height	H (m)	9.94	2.0
Area ratio	A_R/Ld	1/60	1/26.5
Aspect ratio	λ	1.5	1.7
Propeller			
Diameter	D (m)	6.5	1.9
Pitch ratio	P/D	0.65	1.0

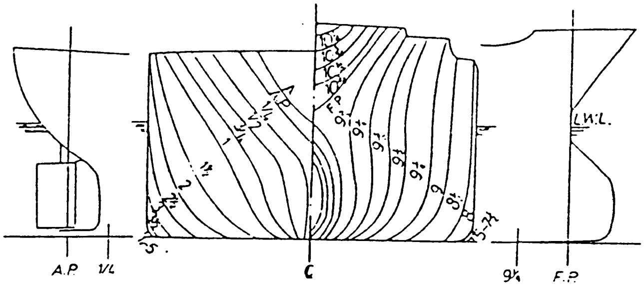


Fig. 3 Body plan and hull end profiles(ore carrier)

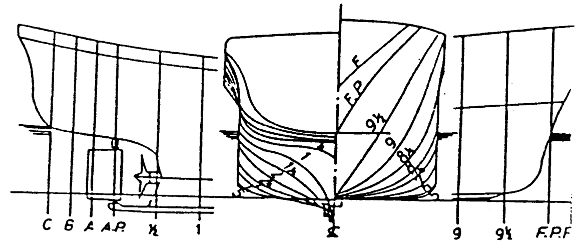


Fig. 4 Body plan and hull end profiles(fishing boat)

Table 2 Coefficients of characteristics of ship dynamics, steering gear and power unit

items	ore carrier	fishing boat
a'_{vv}	0.0282	0.0453
a'_{rr}	0.8290	0.6166
$a'_{\delta\delta}$	0.1316	0.3008
T'_1	6.86	2.45
T'_2	0.35	0.29
T'_3	0.78	0.72
K'	2.48	2.05
T_E	2.5 sec	2.5 sec
$\dot{\delta}_{max}$	3.0 deg / sec	3.0 deg / sec
$2\delta_b$	1 deg	1 deg
$\dot{\delta}^*$	2 deg/sec	2 deg/sec

4.2 Evaluation of disturbance to a ship

We take irregular wave and fluctuation component of wind as disturbances to a ship. Steady wind effect is not considered because that results in constant adjustment of heading angle, which cannot be controlled by the autopilot with PD control.

Fig. 5 shows the coordinate system and sign definition to be used. Time realization of disturbances to a ship in terms of yaw rate which has been expressed by r_d in Fig. 1, can be evaluated as follows.

$$r_d(t) = \sum_{i=1}^{\infty} \sqrt{2S_r(\omega_i)\,\delta\omega} \cdot \sin(\omega_i t + \varepsilon_i) \tag{10}$$

where $S_r(\omega)$ denotes spectral density function of yaw rate due to wave and wind disturbances, ω encounter circular frequency, $\delta\omega$ infinitesimal interval of ω, ε random phase angle, and subscript i the i-th component. $S_r(\omega)$ consists of both terms of $S_{rw}(\omega)$ and $S_{ru}(\omega)$, where $S_{rw}(\omega)$ is due to irregular wave, and $S_{ru}(\omega)$ due to wind fluctuation.

$S_{rw}(\omega)$ can be predicted by following equation.

$$S_{rw}(\omega) = \omega^2 \cdot S_w(\omega) \cdot \left[\frac{\psi_a}{\zeta_a}(\omega) \right]^2 \tag{11}$$

where $S_w(\omega)$ denotes the encountered wave spectrum, and $[\psi_a/\zeta_a(\omega)]$ response amplitude operator of yaw to regular wave. $S_w(\omega)$ is predicted from ISSC or ITTC wave spectrum and the relation between encounter circular frequency and wave circular frequency. $[\psi_a/\zeta_a(\omega)]$ is predicted from seakeeping theory such as strip method[11].

$S_{ru}(\omega)$ can be calculated by following equation.

$$S_{ru}(\omega) = S_\delta(\omega) \cdot |G(j\omega)|^2, \qquad (j = \sqrt{-1}) \tag{12}$$

where $S_\delta(\omega)$ denotes rudder angle spectrum due to fluctuation of wind, and $G(j\omega)$ frequency response function of ship dynamics which has been presented in Fig. 2. $S_\delta(\omega)$ is predicted according to Reference 6 as follows.

$$S_\delta(\omega) = [2 f(\gamma_A) \cdot \{ \overline{U}_T - V\cos\gamma_T\} / V^2]^2 \cdot S_u(\omega) \tag{13}$$

where $f(\gamma_A)$ denotes equivalent rudder angle due to wind force[6], γ_A angle of relative wind, γ_T angle of true wind, $\overline{U}_T$ average wind speed, and $S_u(\omega)$ wind spectrum by fluctuation component, which can be predicted by Davenport as follows.

$$S_u(\omega) = 4.0k \cdot \frac{(\overline{U}_T)^2}{\omega} \cdot \frac{x^2}{(1+x^2)^{4/3}} \tag{14}$$

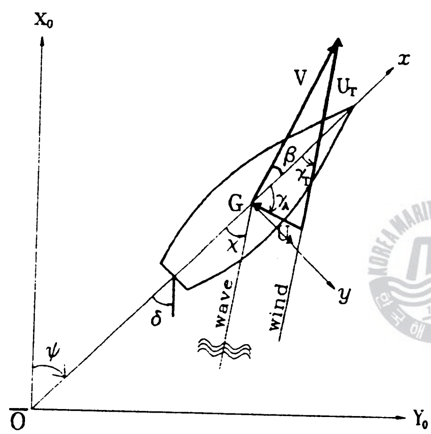
where k denotes surface friction coefficient(in case of sea surface, $k \approx 0.003$), and $x = 600\omega/(\pi \overline{U}_T)$.

In this paper, wind velocity is assumed to change with time around $\overline{U}_T$ 10 m/sec and γ_T is assumed 135 deg. It is also assumed that the long crested irregular waves are generated on sea surface in the same direction as wind with significant wave height(H_w) 2.2 m and the mean wave period(T_1) 5.74 sec, the values of which can be predicted according to Table 3 for corresponding average velocity of wind.

Figs. 6 ~ 7 show response amplitude operators of yaw to regular waves, which are calculated by strip method[11]. Fig. 8 shows ISSC wave spectrum, and Fig. 9 Davenport wind spectrum for $\overline{U}_T$ 10 m/sec. In Figs. 6 ~ 8 ω_0 denotes wave circular frequency, and F_n Froude number. Fig. 10 ~ 11 show disturbance spectra due to wave and wind fluctuation which are calculated by eqs.(11) ~ (12). Fig. 12 ~ 13 show the predicted time histories of disturbances in terms of yaw rate. We attempt to calculate the spectrum from sampled data of time history of disturbances using Blackman-Tukey method[12] in order to validate that the predicted time history of disturbance has the same statistical characteristics as original spectrum. Fig. 14 ~ 15 show comparison of original spectrum with calculated spectrum from sampled data of the time history shown in Figs. 12 ~ 13. From Figs. 14 ~ 15, We can say that time history of disturbances due to wave and wind fluctuation has reasonably been simulated from disturbance spectra, and that those certainly look realistic.

Table 3 Sea states(WMO code 1100)

Beaufort (wind scale)	$\overline{U}_T$ (m/sec)	H_w(m)	T_1(sec)
1	0.95	0.1	1.2
2	2.50	0.2	1.7
3	4.45	0.6	3.0
4	6.75	1.0	3.9
5	9.40	2.0	5.5
6	12.35	3.0	6.7
7	15.55	4.0	7.7
8	19.00	5.5	9.1
9	22.65	7.0	10.2
10	26.50	9.0	11.6
11	30.60	11.5	13.1
12	34.85	14.0	14.1



G : center of gravity
V : ship speed
U_T : true wind speed
U_A : apparent wind speed
β : drift angle
χ : encounter angle of wave
γ_T : angle of true wind
γ_A : angle of relative wind off bow

Fig. 5 Coordinate system and sign definition

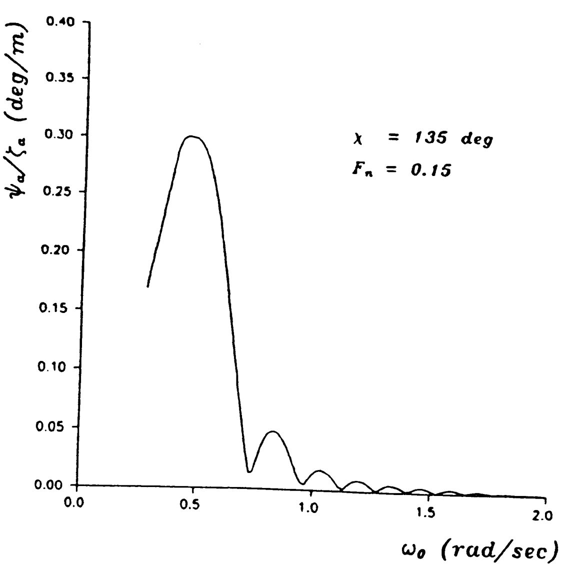


Fig. 6 Response amplitude operator of yaw(ore carrier)

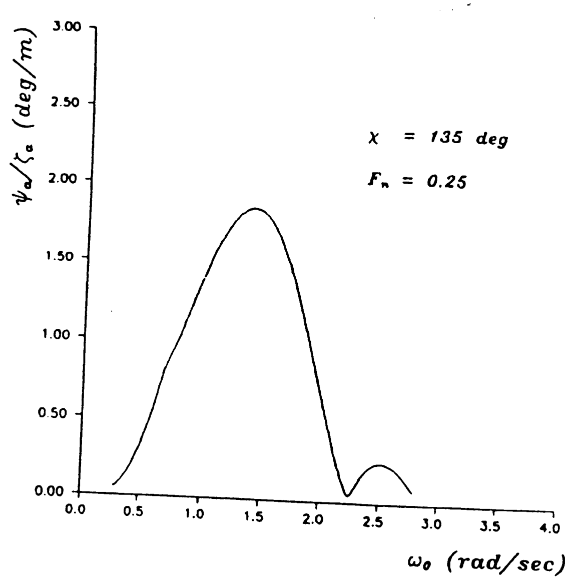


Fig. 7 Response amplitude operator of yaw(fishing boat)

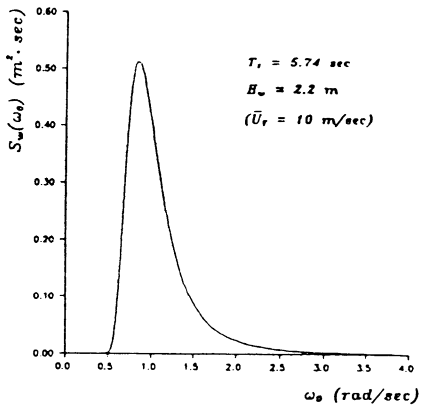


Fig. 8 ISSC wave spectrum

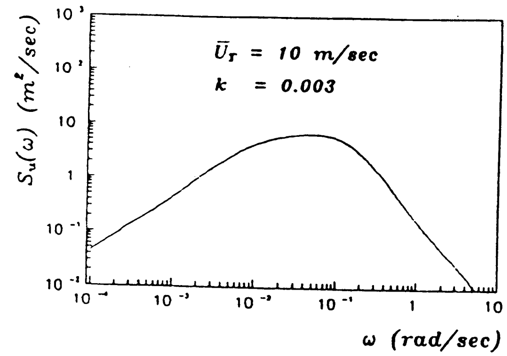
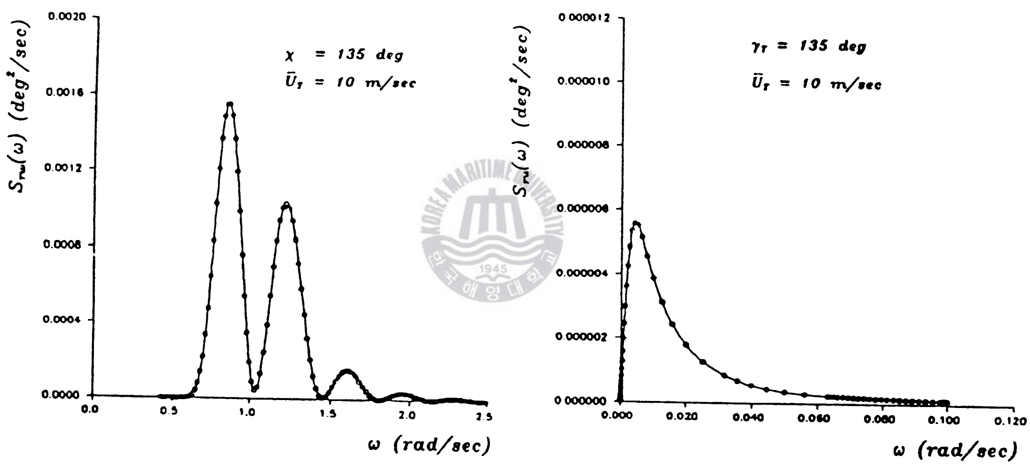
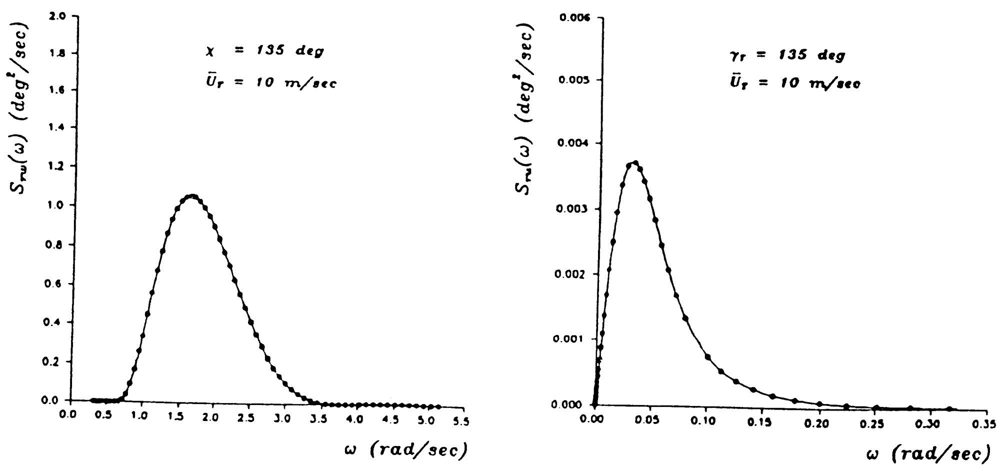


Fig. 9 Davenport wind spectrum



(a) wave (b) wind

Fig. 10 Disturbance spectrum due to wave & wind(ore carrier)



(a) wave (b) wind

Fig. 11 Disturbance spectrum due to wave & wind(fishing boat)

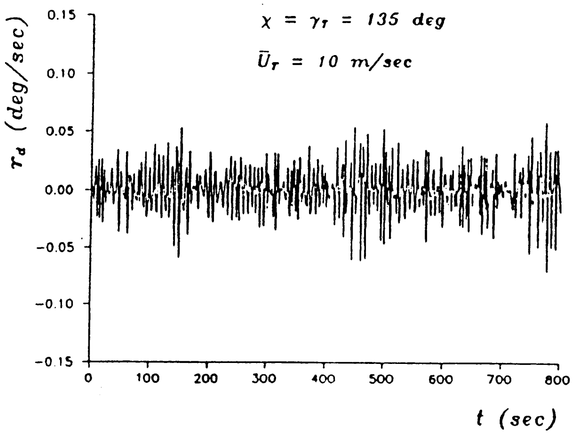


Fig. 12 Time history of disturbance due to wave and wind (ore carrier)

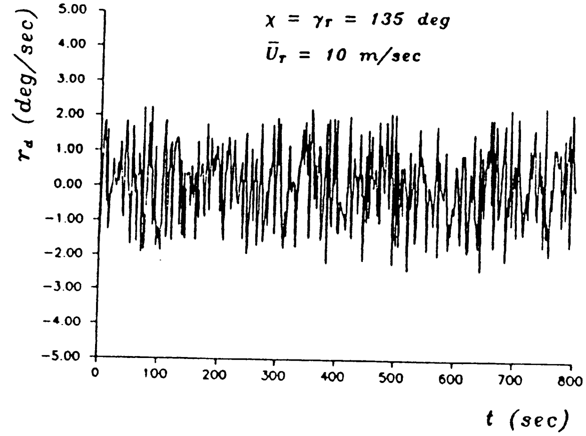
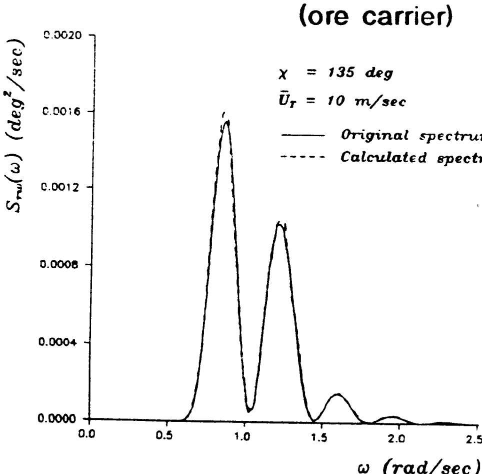
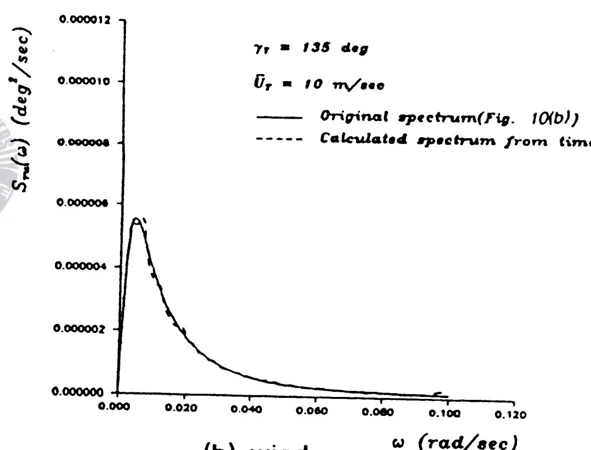


Fig.13 Time history of disturbance due to wave and wind (fishing boat)

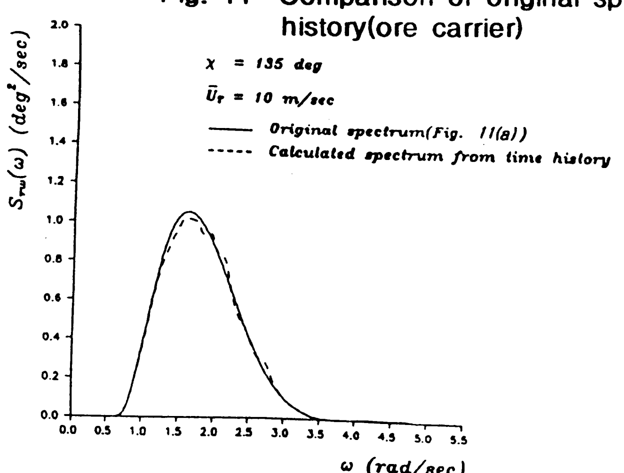


(a) wave

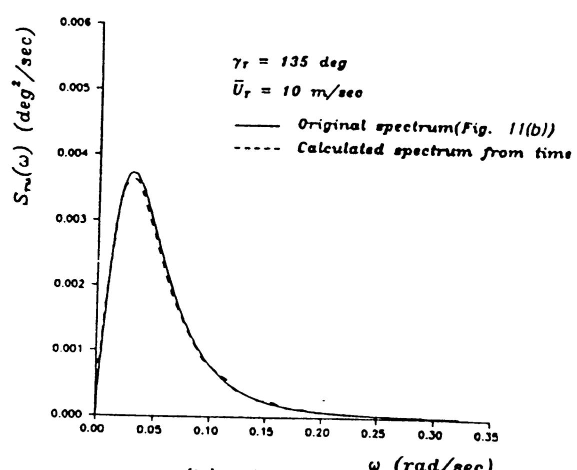


(b) wind

Fig. 14 Comparison of original spectrum with calculated spectrum from time history(ore carrier)



(a) wave



(b) wind

Fig. 15 Comparison of original spectrum with calculated spectrum from time history(fishing boat)

4.3 Numerical calculation of propulsive energy loss and discussion

Figs. 16 ~21 show the calculation results of parametric sensitivity of the linear or non-linear control constants of autopilot to propulsive energy loss in terms of performance index under given sea states. In these figures, the abscissa represents time constant of yaw rate control, the value of which ranges from 0 to 100 sec, the ordinate performance index in percent. The calculation results are illustrated with various marks, and some solid marks mean the starting point of instability of over-all, automatic steering system.

Figs. 16 ~17 show the influence of time constant of low-pass filter on J on condition that rudder gain and dead band width of weather adjustment are constant. it is noticed that the larger T_{cr} in fishing boat and the smaller T_{cr} in ore carrier result in the smaller J especially in the region of somewhat large values of T_D. Figs. 18 ~19 show the influence of b on J on condition that T_{cr} and K_P are constant. From these figures, it is noticed that the larger b in fishing boat and the smaller b in ore carrier result in the smaller J especially in the region of somewhat large values of T_D. This trend is considered to result from that the yaw rate disturbances on small fishing boat are more excessive than those on ore carrier, even though the sea states are unchanged. Figs. 20 ~21 show the influence of K_P on J on condition that T_{cr} and b are constant. From these figures, it is noticed that the smaller K_P in fishing boat results in the smaller J and the better stability of over-all system, and that the ore carrier is not so remarkably affected in J by K_P.

Through the above numerical calculation and examination into that, we can say that the effect of control constants of autopilot on propulsive energy loss has almost opposite tendency between small fishing boat and ore carrier, and that the correct combination of control constants is expected to reduce the loss of propulsive energy. So, the control constants of autopilot for the most suitable adjustment can be decided according to the present method.

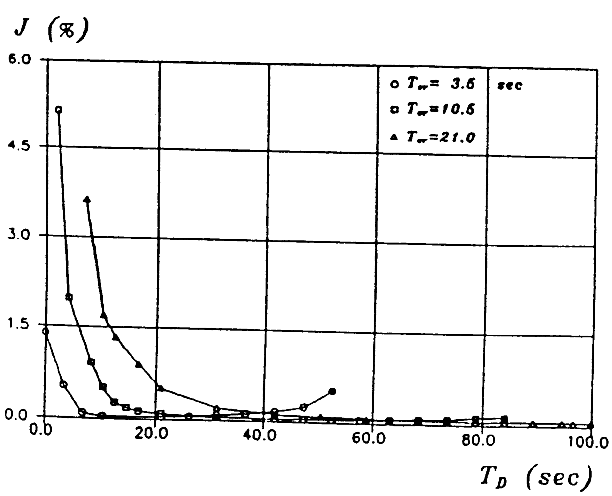


Fig. 16 The effect of filter time constant on propulsive energy loss(fishing boat, K_P = 0.5, b = 1.0 deg)

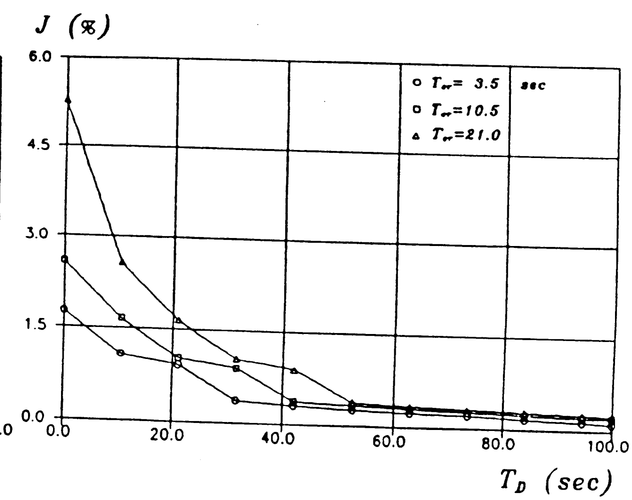


Fig. 17 The effect of filter time constant on propulsive energy loss(ore carrier, K_P = 0.5, b = 1.0 deg)

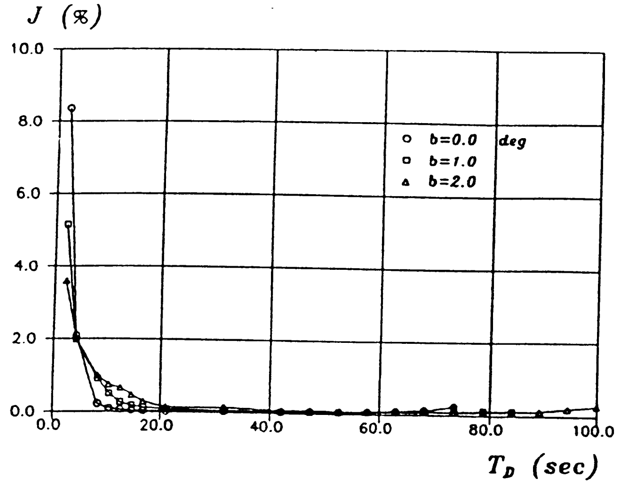


Fig. 18 The effect of weather adjustment on propulsive energy loss(fishing boat, T_{cr} = 10.5 sec , K_P = 0.5)

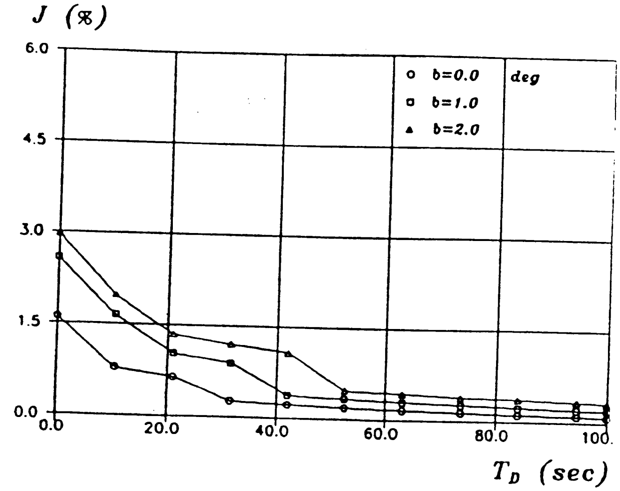


Fig. 19 The effect of weather adjustment on propulsive energy loss(ore carrier, T_{cr} = 10.5 sec , K_P = 0.5)

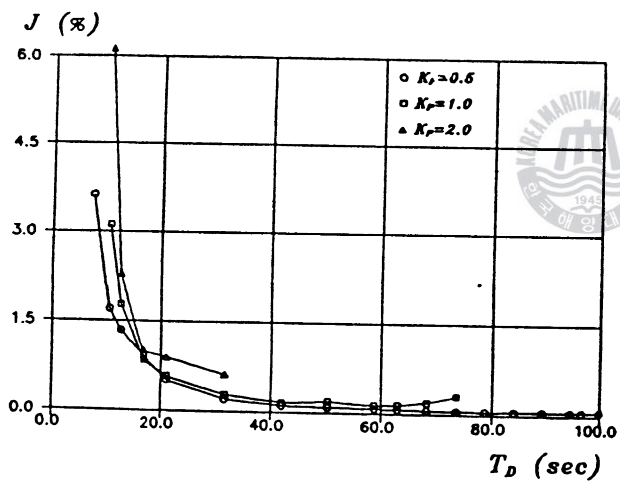


Fig. 20 The effect of rudder gain on propulsive energy loss (fishing boat, T_{cr} = 21.0 sec , b = 1.0 deg)

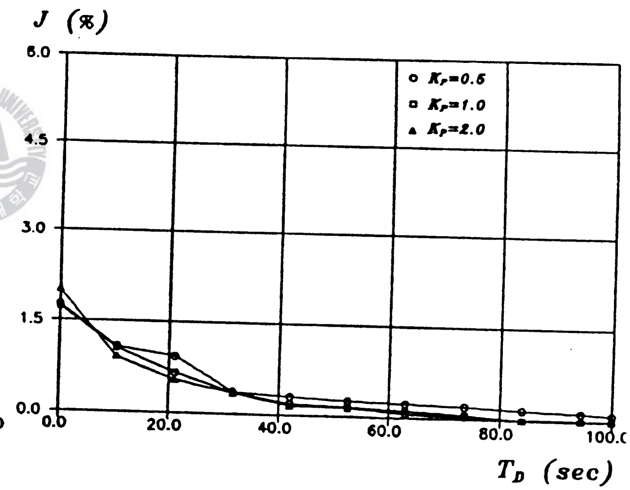


Fig. 21 The effect of rudder gain on propulsive energy loss (ore carrier, T_{cr} = 3.5 sec , b = 1.0 deg)

5. Conclusions

The analytical method to evaluate propulsive energy loss related to automatic steering of ships in the open seas has been explored for the most suitable adjustment of autopilot's control constants. The mathematical model of each element of the composition of automatic steering system has been derived, taking account of a few non-linear mechanisms. The realistic sea and wind disturbances are employed in the analysis. The influences of linear and non-linear control constants of autopilot on propulsive energy loss has reasonably been predicted making use of the present analytical method according to kinds of ship or changes in ship's environment.

This paper was partly supported by KOREA SANHAK FOUNDATION, 1994.

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