PERFORMANCE EVALUATION OF SCHILLING RUDDER AND MARINER RUDDER FOR PURE CAR CARRIERS (PCC) UNDER WIND CONDITION

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Abstract: Simulation of PCC ship with Schilling rudder is developed from full scale sea trial results using data from Voyage Data Recorder (VDR). Constant torque operation of Main engine is considered during simulation, which matches well with full-scale trial results. Simulation of PCC ship for ballast draft and full load draft is developed using Yoshimura's model and Kijima's regression formula. Difference in "Wake Fraction" and "Relative Rotative Efficiency" of Schilling rudder and Mariner rudder for same hull form is considered. Simulations with constant torque operation of Main engine is carried out under various gust wind speed and encounter angle. Gust wind speed is generated using Davenport Spectrum. Fuel consumption and time of travel is calculated in simulations. Based on the simulation results, efficiency of both types of rudder is compared.

1. INTRODUCTION

Since July 2002 all new ships of 3,000 gross tonnage and above are required to be fitted with Voyage Data Recorder (VDR) as per SOLAS regulation. This instrument besides other data, also records Time history of various ship's state. Availability of such data from VDR gives a good opportunity for developing accurate Mathematical model of a ship, provided a model of similar ship type is available or an approximate model is developed using some regression method. Ships with large superstructures, for e.g. PCC carrier, LNG ships and Container carrier etc are easily deviated from their course by wind force. Schilling rudder has been suggested as one of the options for increasing course keeping ability of these ships under wind condition[1]. There is some debate amongst shop designers regarding superiority of Mariner rudder vis-a-vis Schilling rudder from the aspect of model resistance tests. However for ships like PCC, performance under wind conditions is also important. In this paper, mathematical model of a full scale PCC ship fitted with Schilling rudder has been developed. The simulation of mathematical model is validated using VDR data collected from full scale sea trials and voyage data of the vessel. The MMG model is used for carrying out simulations under gust wind conditions for Schilling rudder and Mariner rudder. Inherent superiority of Mariner rudder vis a vis Schilling rudder during straight runs without wind force, is confirmed by constant Main Engine power simulations. Assuming constant Torque operation of Main engine, maneuvering performance and fuel consumption performance of Schilling rudder and Mariner rudder is compared.

2. SHIP MATHEMATICAL MODEL

2.1 Ship Particulars and Coordinate System

The principal particulars of the PCC ship are shown in Table 1.

Table 1 Principal particulars

Principal particulars of PCC ship	
Length	190.00 Meters
Breadth	32.20 Meters
Depth	34.20 Meters
Main engine MCR	15130 kW at 100 RPM
Main Engine CSR	12861 kW at 94.7 RPM

Three degrees of freedom model consisting of surge, sway and yaw motion is considered. The coordinate system is shown in Figure 1.

2.2 Equation of Ship Maneuvering Motion

The equations of the ship maneuvering motion are shown in Equation (1).

$$\begin{aligned} m\dot{u}_G - mv_G r_G &= X \\ m\dot{v}_G + mu_G r_G &= Y \\ I_{ZZ}\dot{r}_G &= N - x_G Y \end{aligned} \qquad (1)$$

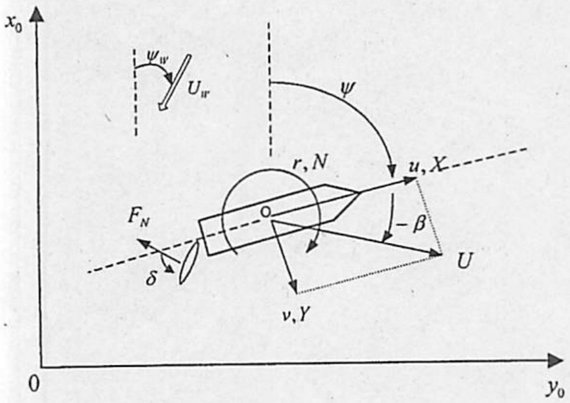

Fig.1 Coordinate system

2.3 Hull Forces and Moments

The external forces X, Y and moment N consisting of hull, hull and propeller, rudder and wind components are expressed as shown in Equation (2).

$$
\begin{aligned}
X &= X_H + X_P + X_R + X_A \\
Y &= Y_{HP} + Y_R + Y_A \\
N &= N_{HP} + N_R + N_A
\end{aligned}
\tag{2}
$$

Subscripts 'H', 'P', 'R', and 'A' refer to Hull, Propeller, Rudder and Wind respectively.

2.4 Mathematical Model for Propeller Thrust

The mathematical model for the Propeller thrust and torque is expressed as shown in Equations (3-4).

$$
\begin{aligned}
X'_P &= 2(1-t_P)K_T(D_P^2 / Ld) / J_S^2 \\
Q_P &= -\rho n^2 D_P^5 K_q
\end{aligned}
\tag{3}
$$

$$
\left.
\begin{aligned}
K_T &= a_1 + a_2 J + a_3 J^2 \\
K_q &= b_1 + b_2 J + b_3 J^2 \\
J &= (1-\omega_{P0}) u / nD_P \\
J_S &= U / nD_P
\end{aligned}
\right\}
\tag{4}
$$

Coefficients of Propeller thrust and torque for the subject PCC are shown in Table 2.

Table 2 Coefficients of propeller model

a_1	0.566	b_1	0.0849	t_P	0.164
a_2	-0.4593	b_2	-0.0403	D_P	6.65 M
a_3	-0.0286	b_3	-0.0232	Pitch	7.159 M

Coefficients of propeller thrust were determined from experiment data of the subject PCC. However, coefficients of propeller torque were not available. They were estimated by selecting a Wageningen-B series propeller[2] whose thrust characteristics are similar to the propeller fitted on the subject PCC ship.

2.5 Mathematical Model for Rudder Forces and Moment

In this paper, Mariner rudder and Schilling rudder are used for the simulation. The perspective view and section of Schilling rudder are shown in Figure. 2.

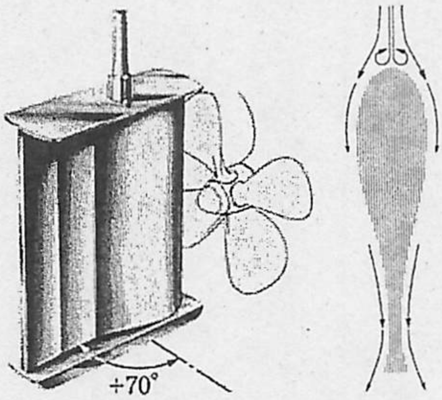

Fig.2 Perspective view and section of Schilling rudder

The unique profile of the Schilling rudder incorporates a rounded leading edge and a fishtail trailing edge. The Schilling rudder is well known for utilizing propeller slipstream to achieve an efficient "side thrust" effect at the ship's stern with operating angles up to 70 degrees. However, for the subject PCC ship at cruising speed, the maximum permissible angle of the Schilling rudder is 35 degrees and at maneuvering speed it is 70 degrees. Since, fuel consumption calculations are carried out at cruising speed, so the maximum rudder angle is considered as 35 degrees in this paper.

When the dimensions of the Schilling rudder and the Mariner rudder are the same, the normal force coefficient for the Schilling rudder can be expressed from that of Mariner rudder by multiplying it by some constant factor[3]. In this paper, for simulations the Mariner rudder and the Schilling rudder have the same size and aspect ratio, so the normal force coefficient for the Schilling rudder is considered 1.3 times of the normal force coefficient of the Mariner rudder.

The coefficients of Mariner rudder's model and Schilling rudder's model are considered same. Coefficients of rudder model from Yoshimura's model experiments have been used [4]. This is because the hull form and rudder aspect ratio of the subject PCC is similar to that of Yoshimura's PCC. The rudder forces and moments are expressed as shown in Equation 5 and 6. The particulars of Yoshimura's rudder model and that of subject PCC are shown in Table 3.

$$X_R' = -(1-t_R)F_N'\sin\delta + (1-t_p)C_{T\delta}F_N'\sin\delta$$
$$Y_R' = -(1+a_H)F_N'\cos\delta \qquad (5)$$
$$N_R' = -(X_R' + a_H x_H')F_N'\cos\delta$$

$$a_H = c_1 + c_2 J + c_3 J^2 \qquad (6)$$

Table 3 Particulars of rudder of Yoshimura' PCC and subject PCC

Coefficients	Yoshimura's model	PCC
A_R / Ld	0.0251	0.0189
D_p / H	0.794	1.0076
t_p	0.162	0.164
Λ	1.177	1.347

Where A_R : Rudder area, L:Length, d:Draft, H:Rudder height, t_p : Thrust deduction fraction, Λ : Rudder aspect ratio respectively.

2.6 Wind Forces and Moments

Forces induced by gust wind are considered in this paper. The expressions of the forces and moment induced by the wind are shown in Equation (7).

$$\left.\begin{aligned} X_A &= \frac{1}{2}\rho_A A U_A^2 C_{FX}(\psi_A) \\ Y_A &= \frac{1}{2}\rho_A A U_A^2 C_{FY}(\psi_A) \\ N_A &= \frac{1}{2}\rho_A A U_A^2 L C_{MZ}(\psi_A) \end{aligned}\right\} \qquad (7)$$

Where, C_{FX}, C_{FY}, C_{MZ} are wind force coefficients

For 0 to 60 degrees encounter angle, the wind forces acting on the PCC were obtained from wind tunnel experiments carried out by Matsumoto [5]. Fujiwara's formula [6] is used to estimate wind forces and moment for 60 to 180 degrees encounter angle.

The wind forces and moment obtained from Fujiwara's formula are modified based on the results from the wind tunnel experiment, so as to obtain a smooth and continuous extension of the curve from the experiment. The wind resistance coefficients C_{FX}, C_{FY}, C_{MZ} which are used in numerical simulations are shown in Figure. 3 as functions of the encounter wind angle.

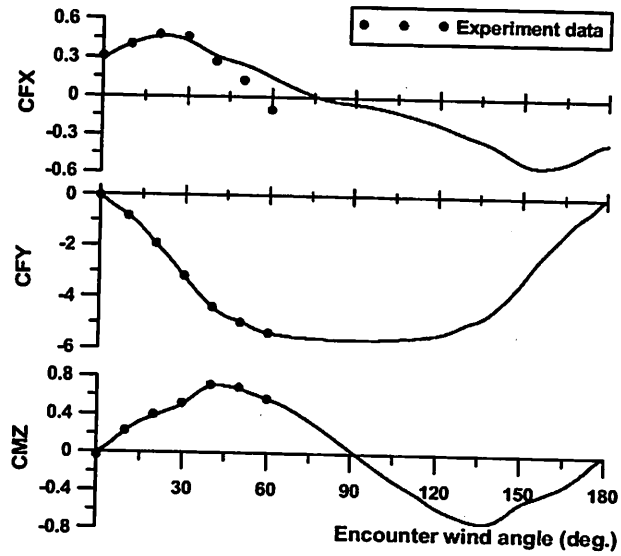

Fig.3 Coefficients of wind resistance

Gust wind was generated using Davenport Spectrum [7] shown in equation (8).

$$S_z(f).df = 4.0\kappa \nabla_1^2 \frac{x}{(1+x^2)^{4/3}} dx$$

$S_z(f)$ – Power Spectrum at height z (8)
f – Frequency (cycles per second)
∇_1 – Velocity at standard reference height of 10 m
κ – Drag Coefficient referred to mean velocity at 10 m
x – $1200 f/\nabla_1$ where f/∇_1 is in cycles per metre

Admittance coefficient was not used, since same mean wind speed was used for generating gust wind for simulation with Schilling and Mariner rudder respectively.

2.7 Constant Torque Simulation of Main Engine

During the full scale sea trials it is observed that propeller RPM varies during Z test and Turning test. By assuming constant Torque operation of Main engine, the propeller RPM drop can be simulated. Propeller RPM drop is calculated using equation (9) [8].

$$2\pi J_{PP}\dot{n} + \rho n^2 D_P^5 K_q(J_P) = Q_P \qquad (9)$$

When rudder angle is given there is a drift, ship's drift induces a variation in "Wake fraction", using this relation drop in propeller RPM can be simulated.

The relation between Main engine torque and Propeller torque is shown in equation (10) [9].

$$r\eta_t\eta_R Q_E = Q_P, \quad (10)$$

Where

r : Gear ratio, η_t : Shaft transmission efficiency

η_R : Relative rotative efficiency

Here, the Propeller and Main engine are turning at same speed, so Gear ratio is equal to 1.0. In this study the main objective is to compare the efficiencies of Mariner and Schilling rudder respectively, so "Shaft transmission efficiency (η_t)" for both systems is assumed as equal to 1.0.

2.8 Schilling Rudder and Mariner Rudder

To know the difference between Mariner rudder and Schilling rudder, 4.0 m VLCC model ship test results were referred [10]. The model tests were carried out for determining "Resistance", "Wake fraction", "Relative rotative efficiency" of the ship with Mariner rudder and Schilling rudder respectively, for various speeds. From model test results, it is observed that for same hull, resistance of the ship with either type of Schilling rudder or Mariner rudder is same. However, "Wake fraction" and "Relative rotative efficiency" for the two rudder types are different. "Wake fraction" determined for the model ship was scaled up to PCC ship size using ITTC 78 scaling formula[11] as shown in equation (11).

$$w_S = t_p + 0.04 + (w_M - t_p - 0.04)\frac{(1+k)c_{FS} + \Delta c_F}{(1+k)c_{FM}} \quad (11)$$

Difference in "Wake fraction" between Schilling rudder and Mariner rudder were thus determined.

"Wake fraction" of PCC ship with Schilling rudder at different drafts was obtained from shipbuilder. "Wake fraction" of PCC ship with Mariner rudder was estimated by applying the "Difference" value calculated earlier.

"Relative rotative efficiency" values were used from the model test results. The values are shown in Table 4 and 5 respectively.

Table 4 Relative Rotative Efficiency

Relative rotative efficiency (η_R)	
Schilling	1.039
Mariner	1.058

Table 5 Wake fraction

Wake fraction (1-w_s) for PCC ship					
		Sea Trial	Ballast	Full Load	Remarks
Draft (m)		6.97	7.66	9.80	
Schilling	1-ws	0.816	0.818	0.823	Estimated by Shipyard
Mariner	1-ws	0.832	0.833	0.838	Using model test results

2.9 Fuel Consumption Calculation

If Main engine torque and RPM are known, the Power and fuel consumption can be calculated using equation (12).

$$Power = 2\pi n Q_E$$

$$\text{Fuel Consumption} = \text{SFOC*Power*Time} \quad (12)$$

It may be noted that for cruising speeds, SFOC for diesel engines can be assumed as constant. Here the value assumed is 165.0 grams/kW-Hour.

2.10Determination of Resistance Coefficient

Speed data for various engine powers, engine RPM and ship draft were available. Several simulations corresponding to above RPM, Speed and Ship draft were carried out by varying the resistance coefficient X'_o, published by Yoshimura. From simulation results, optimum values of X'_o for the subject PCC were obtained by comparing results of simulation and full scale trials. The simulation results with optimum value of X'_o are shown in Table 6.

It may be observed that ship speed from simulation matches well with the actual measured speed. Accuracy is more when average of actual speed in opposite direction is considered, while error is more when actual speed is considered only in one direction. This is because error due to current and wind get minimized when two runs in opposite direction are considered. The Main engine powers estimated from simulations are reasonable as compared to actual power of ship's Main engine shown in Table 1. It may be noted that X'_o is reasonably well determined for ballast and full load draft, this is to be noted particularly because fuel consumption simulation, in the latter part of this paper, are carried out for ballast draft and full load draft. Comparison of simulation and actual speed trials for 99.5 RPM case is shown in Figure 4.

Table 6 Speed simulation

Sr. No.	Ship draft (Meters)	RPM (Simulation and VDR data)	Mean speed from simulation (m/s)	Main engine power (kW) from simulation	Speed from VDR data (m/s)	Remarks
1	6.97	84.5	9.09	8650.21	9.34	Average of 2 runs in opposite direction
2	6.97	94.5	10.17	12096	10.33	- do -
3	6.97	99.5	10.71	14126	10.89	- do -
4	6.97	104.5	11.23	16396	11.32	- do -
5	7.80	82.70	8.47	8204	9.52	Voyage data (one direction)
6	8.95	89.50	9.00	11228	9.21	Voyage data (one direction)

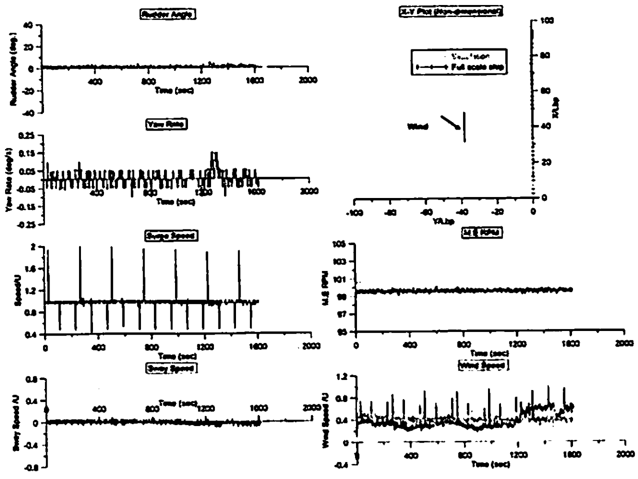

Fig.4 Simulation of straight run at 99.50 RPM

2.11 Maneuvering Trials Simulation

During simulation of maneuvering trials, the resistance coefficient as determined in earlier section was used. For simulating the maneuvering trials, accurate values of sway and yaw hydrodynamic coefficients have to be determined. Initially, sensitivities of all Yoshimura's hydrodynamic coefficients for the subject full scale PCC ship were calculated. Sensitivity analysis was done for 10/10, 20/20 Zig Zag tests and 35^0 Turning tests. The sensitivity formula is shown in Equation 13-15.

$$Sensitivity_{Surge} = \frac{\left.\int_{Test\ Start}^{Test\ End} |u|\,dt\right|_{Hyd.Coeff=x} - \left.\int_{Test\ Start}^{Test\ End} |u|\,dt\right|_{Hyd.Coeff=1.20x}}{\left.\int_{Test\ Start}^{Test\ End} |u|\,dt\right|_{Hyd.Coeff=x}} \times 100 \quad (13)$$

$$Sensitivity_{Sway} = \frac{\left.\int_{Test\ Start}^{Test\ End} |v|\,dt\right|_{Hyd.Coeff=x} - \left.\int_{Test\ Start}^{Test\ End} |v|\,dt\right|_{Hyd.Coeff=1.20x}}{\left.\int_{Test\ Start}^{Test\ End} |v|\,dt\right|_{Hyd.Coeff=x}} \times 100 \quad (14)$$

$$Sensitivity_{Yaw} = \frac{\left.\int_{Test\ Start}^{Test\ End} |r|\,dt\right|_{Hyd.Coeff=x} - \left.\int_{Test\ Start}^{Test\ End} |r|\,dt\right|_{Hyd.Coeff=1.20x}}{\left.\int_{Test\ Start}^{Test\ End} |r|\,dt\right|_{Hyd.Coeff=x}} \times 100 \quad (15)$$

The results of sensitivity analysis are shown in figure 5.

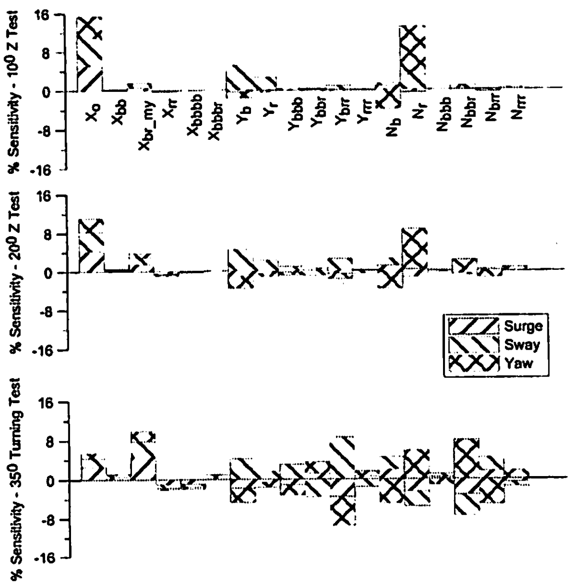

Fig.5 Sensitivity analysis

The hydrodynamic coefficients corresponding to sea trial draft were estimated by suitably changing Yoshimura's hydrodynamic coefficients, based on the result of Sensitivity Analysis. The simulations of maneuvering trials with the new set of coefficients are shown in Figure 6-8.

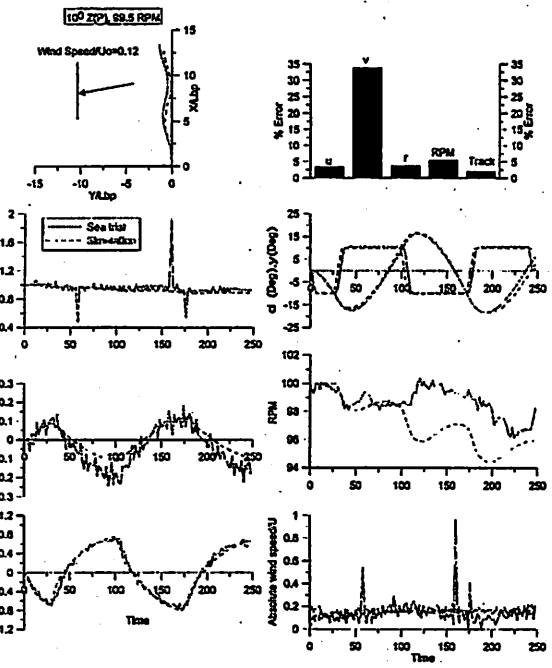

Fig.6 10/10 P Z Test

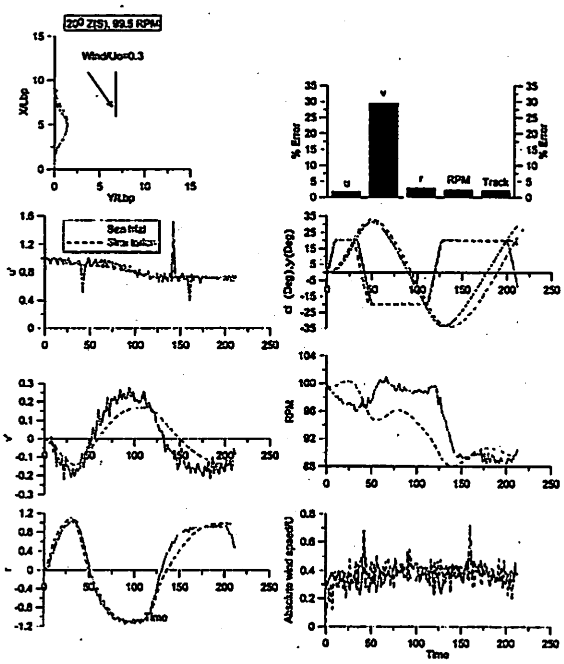

Fig.7 20/20 Stbd Z Test

It is observed that simulations compares well with trial results. In Zig Zag tests, variation in sway speeds is slightly higher, however it can be seen that the ship data has lot of noise. Variation in propeller RPM during turning tests is simulated well. In 20/20 Zig Zag tests, variation in propeller RPM follows the same pattern as that of trials. In case of 10/10 Zig Zag tests, the RPM variation has some difference. This is because ship has engine control system which responds to variation in external loads. During simulation engine control system was not used. It may also be observed that gust wind generated by Davenport Spectrum matches well with actual measured values.

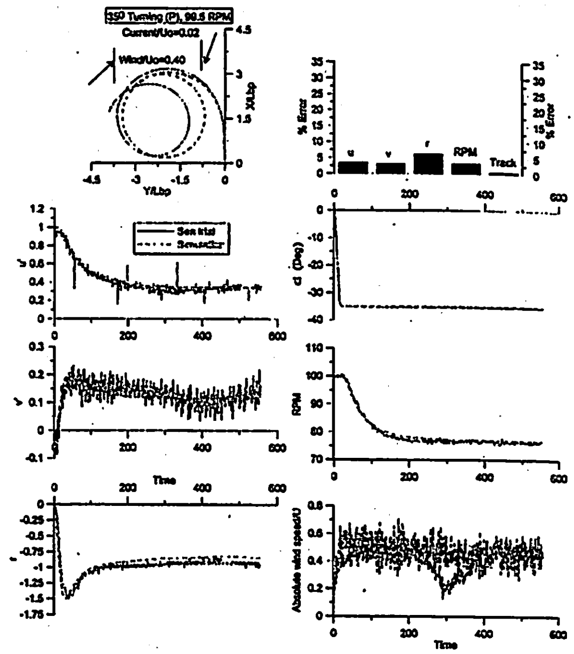

Fig.8 35^0 Port Turning test

The hydrodynamic coefficients obtained above are for sea trial draft. However, during operation vessel mainly operates at ballast draft and full load draft, which are considerably higher. In order to determine hydrodynamic coefficients for the ballast draft and full-scale draft, Kijima's regression method[12] was used. Kijima's method was used for calculating hydrodynamic coefficients at sea trial draft, ballast draft and full scale draft respectively. As accurate values of hydrodynamic coefficients at sea trial draft are known from simulations, the correction factor for hydrodynamic coefficient predicted from Kijima's regression formula at sea trial draft was estimated. This correction factor was then applied to hydrodynamic coefficients determined by Kijima's method for ballast draft and full load draft. So a set of hydrodynamic coefficients for sea trial draft, ballast draft and full load draft for the subject PCC ship were obtained. An example of calculation is shown in Figure 9 and Figure 10.

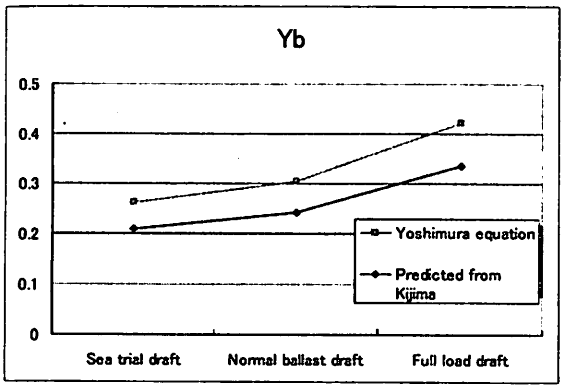

Fig.9 Determination of Y_β

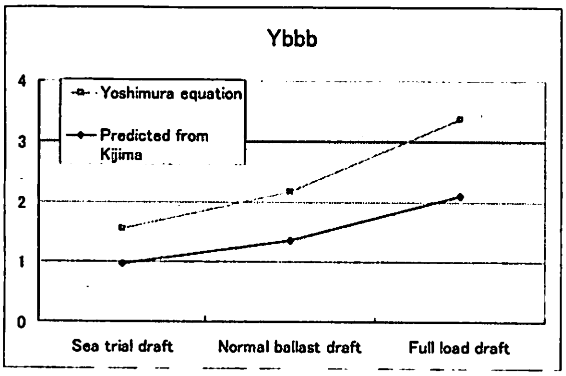

Fig.10 Determination of $Y_{\beta\beta\beta}$

3. SIMULATIONS WITH SCHILLING RUDDER AND MARINER RUDDER

3.1 Constant Power Simulation Without External Forces

Straight line simulations were carried out with both Mariner rudder and Schilling rudder at constant power of Main engine to determine the speed achieved. Values of resistance coefficient $X_o^{'}$, wake fraction and relative rotative efficiency determined earlier were used for simulations. The results are shown in Table 7.

It can be observed that for same Main engine power, ship fitted with Mariner rudder has higher RPM as compared to Schilling rudder. Speed of ship fitted with Mariner rudder is also marginally higher as compared to Schilling rudder. Above results are as per expectation, since Mariner rudder is considered superior to Schilling rudder for straight runs.

Table 7 Speed simulation for Mariner rudder and Schilling rudder

No	Ship draft (m)	RPM	Mean speed (m/s)	Main engine power (kW)	Condition
1	7.66	85.59	8.905	9000.0	Mariner rudder
2	7.66	84.62	8.882	9000.0	Schilling rudder
3	9.80	90.26	8.779	11500.0	Mariner rudder
4	9.80	89.28	8.75	11500.0	Schilling rudder

3.2 Maneuvering Simulation Without External Force

Zig Zag simulations without any external forces were carried out for both Schilling and Mariner rudder. Nomoto's constant K and T were calculated for Zig Zag tests [13]. The K-T graph is shown in Figure 11.

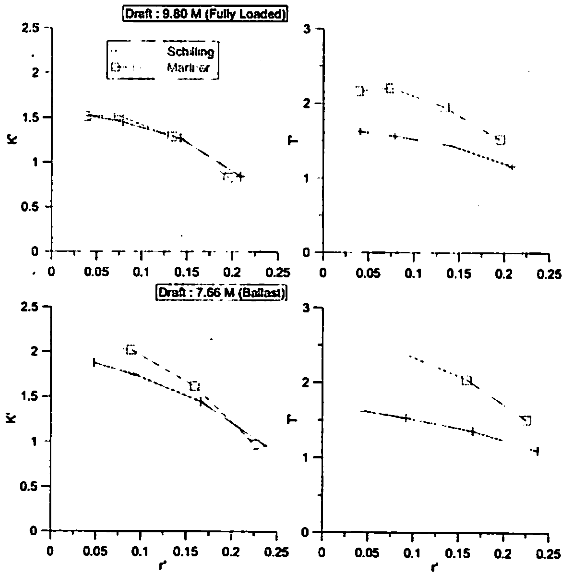

Fig.11 K-T from Zig Zag simulation

It is well known that 'K' represents turning ability while 'T' represents course stability of a ship. It can be observed that time constant (T) of Schilling rudder is superior to Mariner rudder in ballast as well as loaded draft. Gain (K) is comparable for both rudders in fully loaded draft, however Gain (K) of Mariner rudder is marginally higher for ballast draft. Time series of 20/20 Port Zig Zag test is shown in Figure 12 for better understanding.

It can be observed that even with lower Propeller RPM and speed, the Sway and Yaw speed of Ship fitted with Schilling rudder is higher as compared to Mariner rudder. It can also be observed that ship with Schilling rudder completes the Zig Zag test faster as compared to ship fitted with Mariner rudder. This shows that even with higher Propeller RPM and speed, maneuverability of ship fitted with Mariner rudder is less than that of ship fitted with Schilling rudder.

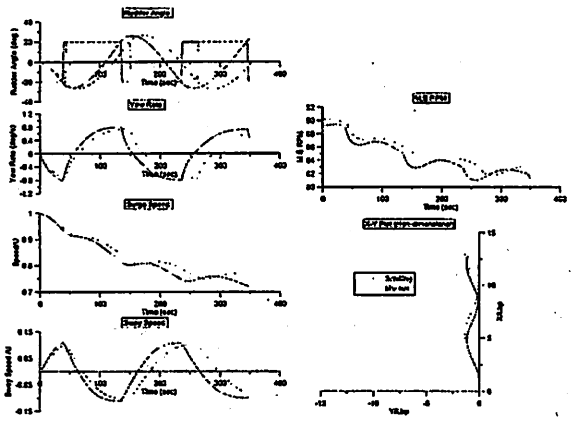

Fig.12 20/20 P Zig Zag test simulation

3.3 Simulations under Wind

With above model, where speed and RPM of Mariner rudder is higher than Schilling rudder, course-keeping simulations were carried out under gust wind conditions at various wind directions.

Simulations were carried out for constant time interval. Mean Rudder angle, Mean drift angle, Straight line distance traveled and fuel consumed were calculated. The results of simulation are shown in Figure 13 and Figure 14 respectively.

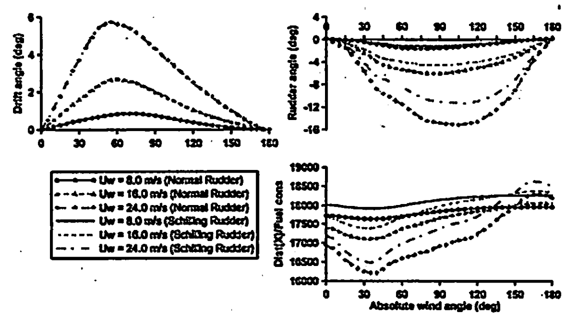

Fig.13 Summary of simulations in ballast condition

The results are reasonable in the sense that for quartering and following winds, fuel efficiency is higher because of additional propelling thrust due to wind. It can be observed that fuel consumption is higher for loaded draft as compared to ballast draft. More important of all, it can be observed that straight line distance traveled for unit amount of fuel consumed is higher for Schilling rudder as compared to Mariner rudder.

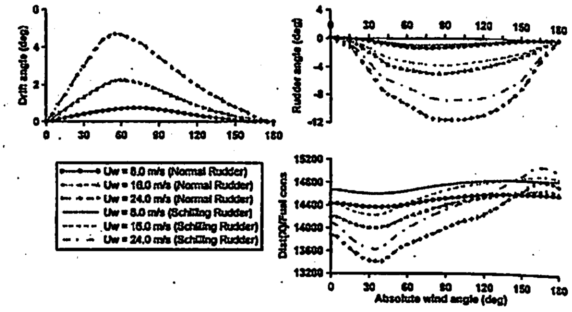

Fig.14 Summary of simulations in loaded condition

To understand this phenomenon more clearly, detailed analysis is carried out for wind encounter angle 120 Degrees and mean wind speed 30 m/s. Constant distance simulation was carried out for both Mariner rudder and Schilling rudder. The results are shown in Figure 15 and Figure 16 respectively.

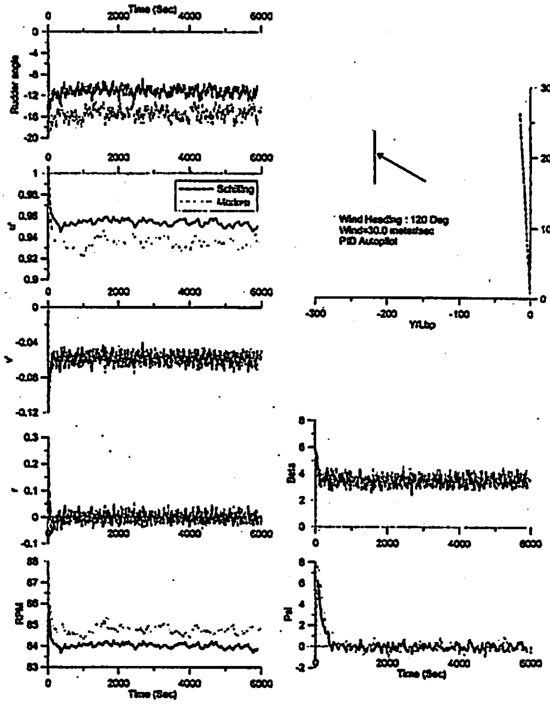

Fig.15 Simulation in Ballast draft

From Time Series Data, it can be observed that ship with Schilling rudder uses lower rudder angle to maintain course as compared to ship fitted with Mariner rudder. Because of lower rudder angle, the drop in ship speed with Schilling rudder is less than with Mariner rudder, although the initial absolute speed of ship fitted with Mariner rudder is higher as compared to that of ship fitted with Schilling rudder. Good performance of Autopilot can be observed, since Psi (Heading able) and r (yaw rate) are averaged to zero for the duration of the voyage. The influence of these factors on Fuel consumption and time of travel is shown in Table 8.

It can be observed that for covering same distance, ship fitted with Schilling rudder uses less fuel and also takes less time as compared to ship fitted with Mariner rudder. This trend is followed for various wind rate as well as wind encounter angle.

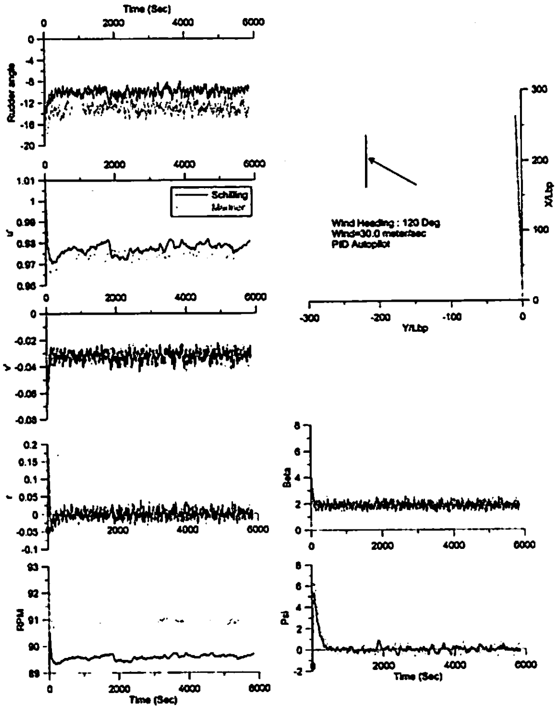

Fig.16 Simulation in Full load draft

Table 8 Comparison of fuel efficiency of Schilling rudder and Mariner rudder

50000 M distance simulation			
		Fuel consumed (MT)	Time (Seconds)
Ball. Draft (7.66 m)	Schilling	2.507	5897
	Mariner	2.596	5999
Full Draft (9.80 m)	Schilling	3.211	5846
	Mariner	3.294	5857

3.4 Autopilot

PID autopilot with velocity gain scheduling[14] was used for course keeping simulations under wind conditions. The PID control and formula for regulator gains are shown in equations 16-18.

$$\delta = K_p(\psi_d - \psi) - K_d\dot{\psi} + K_i\int_0^t(\psi_d - \psi(\tau))d\tau$$

PID Control

Where $K_p > 0$, $K_d > 0, K_i > 0$

ψ_d : Desired Heading, ψ:Actual Heading

$$K_p = \frac{T\omega_n^2}{K}, K_d = \frac{2T\zeta\omega_n - 1}{K}, K_i = \frac{\omega_n^3}{10}\frac{T}{K}$$

ω_n : Ship's Natural Frequency

$0.8 \le \zeta$ (Damping Coefficient) ≤ 1.0

$$\underbrace{\frac{1}{T}}_{\text{Ship dynamics}} < \underbrace{\omega_n\sqrt{1-2\zeta^2+\sqrt{4\zeta^4-4\zeta^2+2}}}_{\text{Closed Loop bandwidth}} < \underbrace{\omega_\delta}_{\text{Rudder Servo}}$$

ω_δ : Rudder Turning Rate (radians/second)

Velocity Gain Scheduling :

$$K = \frac{U}{L_{bp}}K', \; T = \frac{L_{bp}}{U}T'$$

To confirm if the fuel efficiency of Schilling rudder is superior to Mariner rudder due to rudder system or Autopilot, sensitivity of the Fuel consumption to Autopilot regulator gains were calculated. The values are shown in Figure 17 and 18.

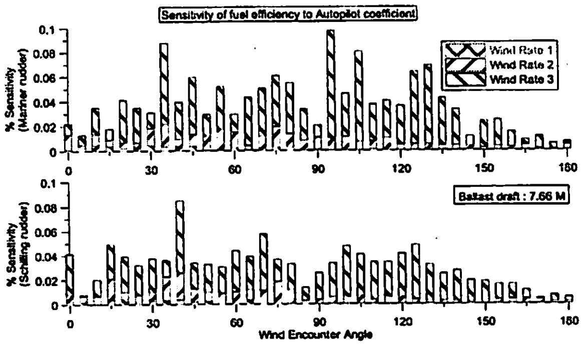

Fig.17 Sensitivity of fuel efficiency to Autopilot coefficients at Ballast draft

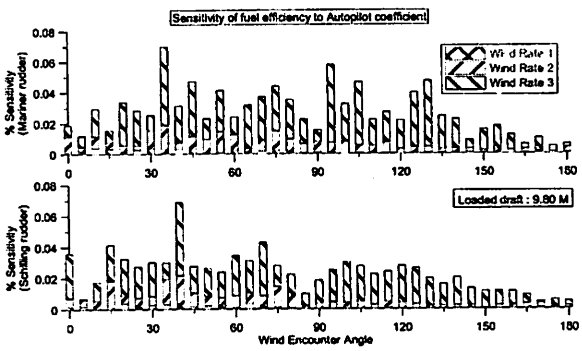

Fig.18 Sensitivity of fuel efficiency to Autopilot coefficients at Full load draft

The sensitivity results are reasonable, since for higher wind rate, the sensitivity is higher. However, the maximum change in fuel consumption is less than 0.1% for ±10% change in regulator gain. The above results show that increased fuel efficiency of ship is only due to the type of rudder system and not due to values of Autopilot regulator gain. From above, it can be concluded that Schilling rudder is superior to Mariner rudder not only from the aspect of maneuvering but also from point of view of fuel efficiency under wind.

4. CONCLUSION

Performance of Shilling rudder and Mariner rudder under various gust wind conditions have been compared. It is observed that without any external force, for same Main Engine power, speed and propeller RPM of ship fitted with Mariner rudder is higher as compared to that of ship fitted with Schilling rudder. Even with lower speed and propeller RPM, maneuverability of ship with Schilling rudder is superior to that of ship with Mariner rudder. Additionally, during course keeping tests at various wind encounter angle and various gust wind, fuel efficiency of ship fitted with Schilling rudder is higher as compared to that of ship fitted with Mariner rudder. During course keeping under wind, ship fitted with Schilling rudder not only covers more distance for unit amount of fuel consumed but also takes less time. From above results, it can be concluded that Schilling rudder is superior to Mariner rudder not only from the aspect of maneuvering but also from the aspect of fuel efficiency under wind conditions.

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