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TURNING MOTION OF A SHIP WITH SINGLE CPP AND SINGLE RUDDER DURING STOPPING MANEUVER UNDER WINDY CONDITION

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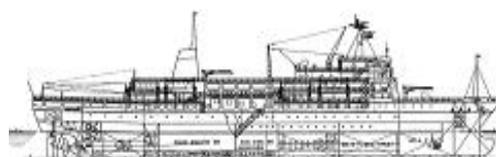
Abstract: This paper describes the results of experimental and simulation studies that aimed at investigating the characteristics of the stopping motion of a ship with a single controllable pitch propeller (CPP) and single rudder. In a full-scale experiment, stopping tests were performed to compare the stopping motion between CPP ships and that of fixed pitch propeller (FPP) ships and the turning motion of a CPP ship was found to be less stable than that of a FPP ship, particularly under windy condition. A simulation study was also conducted to investigate the effect of wind on the stopping motion of CPP ships by which it can be proved that CPP ships are forced to turn her head windward and to drift leeward considerably under beam or quarter wind conditions. Based on the results of these full-scale and simulation studies, a method can be proposed to estimate the critical range of stopping maneuver without tug assistance and effective stopping maneuver for berthing and anchoring under windy condition.

1. INTRODUCTION

During stopping maneuver of CPP ships, unstable yaw moment is often exerted, which introduces a significant reduction in maneuverability [1] [2]. The effect of wind on maneuverability increases at low maneuvering speeds. For shiphandlers, it is important to know the characteristics of the stopping motion of CPP ships and their effective stopping maneuver for berthing and anchoring under windy condition.

From these points of view, full-scale stopping tests for various combination of advance speed and astern rps of propeller were conducted in order to compare the stopping motions between CPP ships and that of FPP ships. The tested ship is a 5,884 G.T. training ship with a single CPP that can also reverse the main diesel engine directly. This system makes it possible to perform a comparative experiment using the same hull and engine under the same condition to investigate the difference of a stopping motion between CPP and FPP ships. Fig. 1 shows the general arrangement and principal particulars of the ship. The characteristics of the turning motion of the ship during stopping maneuver under windy condition were investigated by simulation using the MMG type mathematical model.

This paper describes the results of the experimental and simulation studies on the stopping motion of a ship with single CPP and single rudder and proposes an effective stopping maneuver of CPP ships under windy condition.



Principal Particulars	
Length: Lpp (m)	105.00
Breadth: B (MLD, m)	17.90
Depth: D (MLD, m)	10.80
Cb	0.5186
draft: d (m)	5.96
Displacement (ton)	5827
Prop. Brake No.	4 (CPP)
Prop. Dia.: Dp (m)	4.70
P.R. (Brake Angle)	1.050 (25.5°)

Fig. 1 Principal particulars of the test ship

2. COMPARISON OF TURNING MOTION BETWEEN CPP AND FPP

Full-scale stopping tests were performed under almost the same condition at the deep water in both CPP and FPP operation modes. As light breeze was observed during the experiment, the initial course was set into the wind for all stopping tests.

In Fig. 2, non-dimensional stopping time ($t' = t \cdot (U_0 / L)$) are plotted against the initial advancing constant $J_{S0} (= U_0 / (n \cdot P))$, where it can be seen that the stopping time in the CPP mode is mostly shorter than that in the FPP mode.

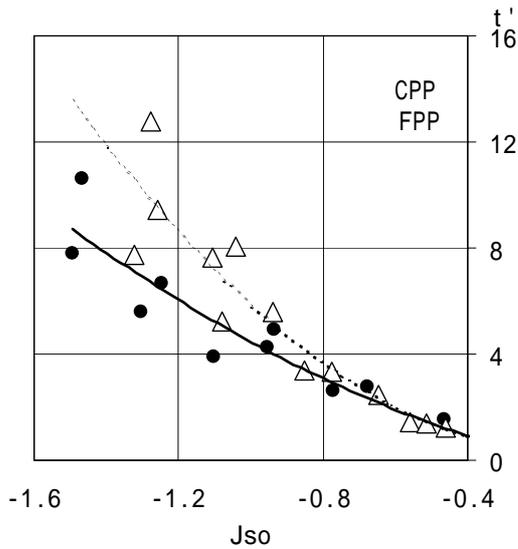


Fig. 2 Comparison of the stopping time between CPP and FPP

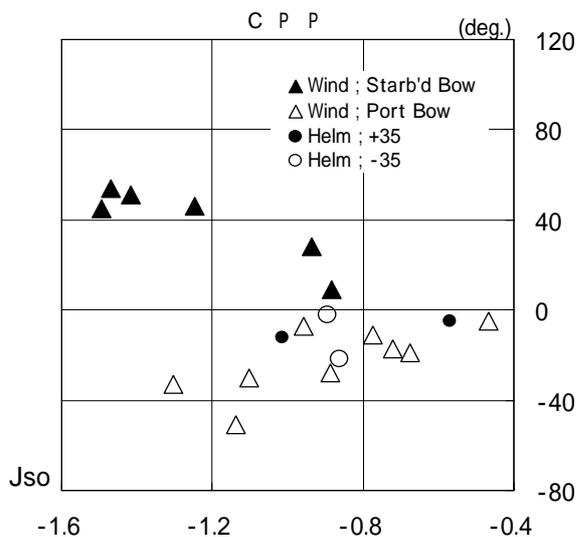
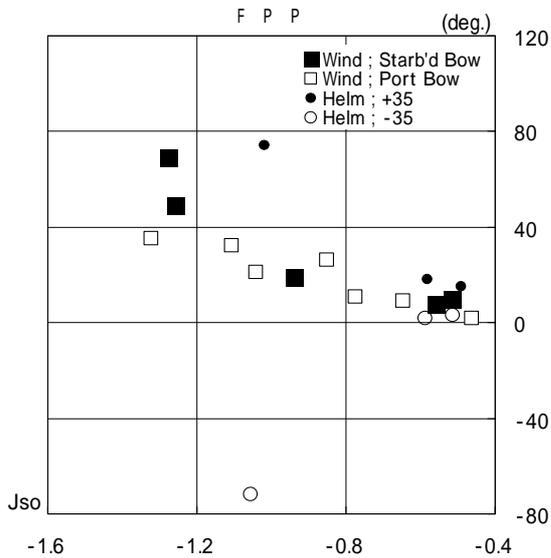


Fig. 3 Comparison of the head turning angle between FPP and CPP

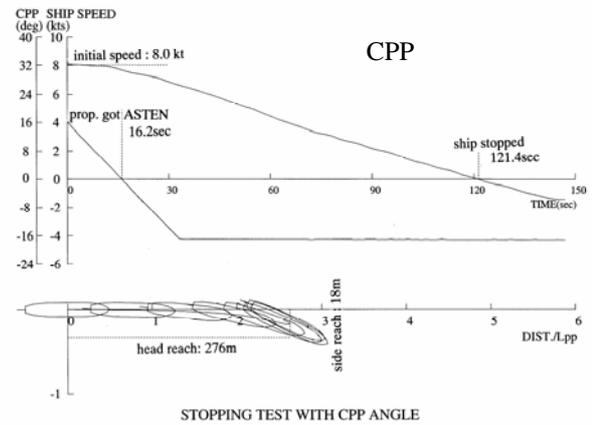
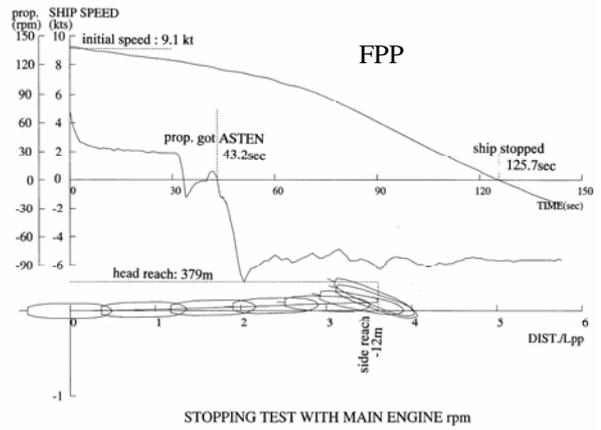


Fig. 4 Comparison of the time history and trajectory between FPP and CPP (8 knots to Full astern)

From this figure, it can be pointed out that the CPP mode is more superior than the FPP mode in stopping ability.

Fig. 3 shows the comparison of final head turning angle (Ψ) at the ship stop. In the figure, results of stopping maneuver in which the propeller was reversed and the maximum rudder angle was applied simultaneously are plotted in addition to those with the rudder a midship rudder both in the CPP and FPP modes.

In the FPP mode, the tested ship makes the typical stopping motion of a right turning single propeller ship i.e. she turns her head to the starboard steadily and the direction of her turning motion can be sufficiently controlled by steering. On the other hand, the turning motion in the CPP mode proved to be less stable than that in the FPP mode and the effect of steering to control the direction of turning motion was not observed. The direction of turning motion in the CPP mode seems to be fixed mainly by the relative wind direction at the initial stage of propeller reversing.

The difference of a transition process from advance thrust to reversing thrust between CPP and FPP is one of the conceivable causes of the unstable turning motion of CPP ships shown in Fig. 3. Fig. 4 shows

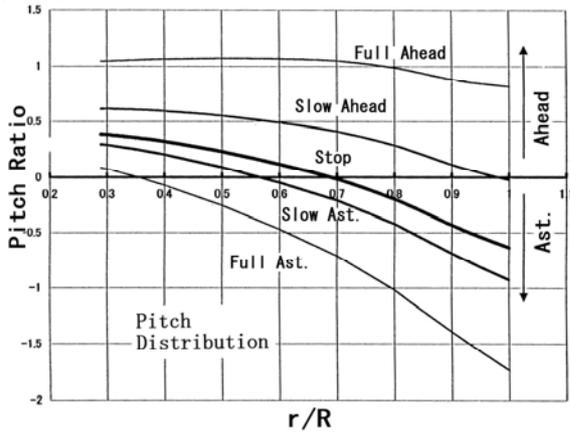


Fig. 5 CPP pitch distribution (test ship)

the time history and trajectory comparisons where the test ship makes full astern operation while proceeding at 4 knots with the CPP mode and the FPP mode. As for a FPP, the propeller is rotated by the advance inertia of the ship at the initial stage of the reversing operation and it gets astern after the revolution reduces to the reversible revolution. Although the rudder force will be decreased during the propeller idling, the ship can be controlled sufficiently by steering. Because of the short transition time from the propeller idling to reversing, the ship's motion after propeller reversing is fixed by the apparent advance coefficient J_{s0} at this transition point. On the other hand, a CPP starts to change the blade angle to a reverse pitch immediately after reversing operation and needs some transition time for attaining the ordered reverse pitch. Since the rudder force is not expected during this transition period, the control of CPP ships by steering is considered to be difficult. Next, the pitch distribution of a CPP is also considered to be a factor of the unstable stopping motion of CPP ships.

The pitch distribution of a CPP depends on the propeller blade angle as in Fig. 5. Though the pitch changes to the reverse side greatly around the tip in the astern blade angle, the small advance pitch remains near the boss, therefore, there is a possibility that the unstable flow is generated around the CPP. Since this turbulent flow in the CPP reversing transforms the flow around the stern and hydrodynamic forces acting on the hull tend to fluctuate with time, it is considered that the direction of turning motion of CPP ships depends on the relative wind direction.

Thus, a measurement of the hydrodynamic forces by model tests seems to be necessary for the clarification of the cause of the unstable turning motion of CPP ships during stopping maneuver.

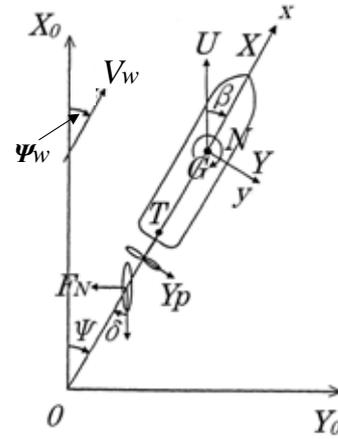


Fig. 6 Coordinate system

3. STOPPING MOTION PREDICTION OF CPP SHIPS

3.1 Mathematical model

The mathematical model for maneuvering motion of CPP ships can be described by the following equations of motion using the coordinate system in Fig. 6.

$$\left. \begin{aligned} m\dot{u} - mvr &= X \\ m\dot{v} + mur &= Y \\ I_{zz}\dot{r} &= N \end{aligned} \right\} (1)$$

The hydrodynamic forces can be expressed by the following equations based on the assumption that the steering is not applied during stopping maneuver.

$$\left. \begin{aligned} X &= X_H + X_P + X_W \\ Y &= Y_H + Y_P + Y_W \\ N &= N_H + N_P + N_W \end{aligned} \right\} (2)$$

where, m : mass of ship

I_{zz} : moment of inertia of ship in yaw motion

u, v, r : axial velocity, lateral velocity, rate of turn

The terms X, Y and N represent the hydrodynamic forces and moment. The subscripts H, P and W refer to the hull, propeller and wind force respectively.

(1) Forces and moment acting on hull

$$\left. \begin{aligned} X_H &= -m_x^i \dot{u} + (\rho/2)LdU^2 \\ &\quad \times \{X_0^i + X_{vv}^i v^2 + (X_{vr}^i - m_x^i) \dot{v} r + X_{rr}^i r^2 + X_{vvv}^i v^4\} \\ Y_H &= -m_y^i \dot{v} + (\rho/2)LdU^2 \\ &\quad \times \{Y_v^i \dot{v} + (Y_r^i - m_y^i) r + Y_{vv}^i v^3 + Y_{vr}^i v^2 r + Y_{vr}^i v r^2 + Y_{rr}^i r^3\} \\ N_H &= -J_z^i \dot{r} + (\rho/2)L^2 dU^2 \\ &\quad \times \{N_v^i \dot{v} + N_r^i r + N_{vv}^i v^3 + N_{vr}^i v^2 r + N_{vr}^i v r^2 + N_{rr}^i r^3\} \end{aligned} \right\} (3)$$

where, m_x , m_y and J_{zz} are the added mass and moment of inertia. X'_0 corresponds to hull resistance coefficients. The term ρ , L and d represent the water density, ship length between perpendiculars and mean draft of ship respectively. The resultant velocity at the center of gravity U , non-dimensional turning rate r' and sway velocity v' are expressed as $U = \sqrt{u^2 + v^2}$, $r' = r(L/U)$ and $v' = v/U$.

(2) Forces and moment induced by propeller
The propeller backing force X_p can be expressed as the function of propeller advance coefficient J_p and blade angle θ_p .

$$\left. \begin{aligned} X_p &= (1-t) \cdot \rho n^2 D_p^4 \cdot K_T(J_p, \theta_p) \\ J_p &= U_p / (n \cdot D_p) \end{aligned} \right\} \quad (4)$$

where, K_T , t , n , D_p and U_p are thrust coefficient, thrust deduction factor, propeller revolution, propeller diameter and propeller advance speed respectively. The lateral force Y_p and yaw moment N_p can be represented as the function of propeller advance coefficient J and blade angle θ_p .

$$\left. \begin{aligned} Y_p &= (\rho/2) L d (nP)^2 \cdot Y'(J, \theta_p) \\ N_p &= (\rho/2) L^2 d (nP)^2 \cdot N'(J, \theta_p) \\ J &= U / (n \cdot P) \end{aligned} \right\} \quad (5)$$

where, P is the propeller pitch.

(3) Wind force and moment

$$\left. \begin{aligned} X_w &= (\rho_a/2) A_T C_X U_R^2 \\ Y_w &= (\rho_a/2) A_S C_Y U_R^2 \\ N_w &= (\rho_a/2) A_S L C_N U_R \end{aligned} \right\} \quad (6)$$

where, ρ_a , U_R , A_T and A_S are air density, relative wind velocity, longitudinal projected area and transverse projected area of hull above water line respectively. C_X , C_Y and C_N represent the coefficients of wind force and moment.

3.2 Hydrodynamic derivatives and coefficients

The hydrodynamic derivatives and coefficients for simulation were measured by the captive model tests using 1/24.48 ($L_{pp}=4.29\text{m}$) model [3]. The obtained hydrodynamic derivatives and coefficients of hull were made non-dimensional using $(\rho/2)LdU^2$ or $(\rho/2)L^2dU^2$ as listed in the table 1. The added mass and moment of inertia are estimated by Motora's charts.

Table 1 Hydrodynamic force derivatives of the hull

X'_0	-0.01251		
X'_{vv}	-0.04573	Y'_v	-0.3805
$X'_{vr} - m'_y$	0.11393	$Y'_r - m'_x$	0.00796
X'_{rr}	0.01861	Y'_{vvv}	-2.30501
X'_{vvv}	0.5269	Y'_{vvr}	-1.647
		Y'_{rr}	-1.09
		Y'_{rrr}	-0.08811
		N'_v	-0.14968
		N'_r	-0.07954
		N'_{vvv}	-0.33502
		N'_{vvr}	-0.77054
		N'_{vrr}	-0.21205
		N'_{rrr}	-0.05025

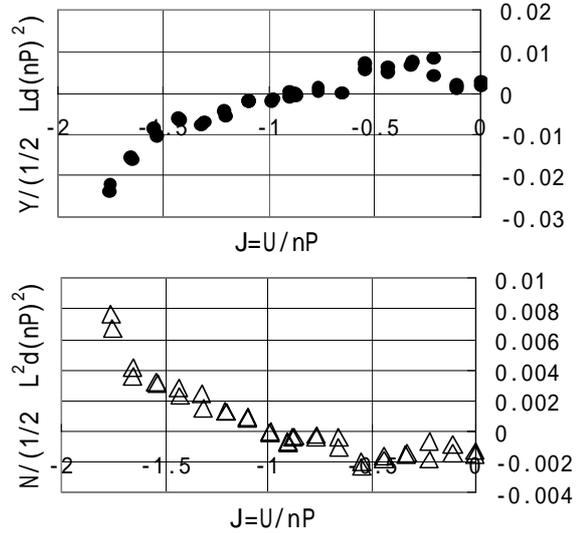


Fig. 7 Force and moment exerted by reversing propeller ($n>0$, $P<0$)

As for the forces and moment induced by propeller reversing, the thrust coefficients were estimated using the 4 quadrant POT result on the reversing blade angle -19 (deg.) and $K_T(J_p, \theta_p)$ data on MAU charts. The thrust deduction coefficient was obtained by the model test. The lateral force and moment were obtained from the captive model tests on the reversing blade angles (-13.5 deg.) as shown in Fig. 7 [3].

The wind force and moment coefficients were derived from a wind tunnel test using the 1.5 m length model [3]. In the wind tunnel test, spires and blocks were used to generate the wind profile on the sea. The obtained wind force and moment coefficients are shown in Fig. 8.

3.3 Validation of stopping motion prediction

The accuracy of the mathematical model of the test ship was confirmed by comparing the simulation results with those of full-scale experiments.

As an example, the comparison of simulated stopping motion and the trial results under the 9 m/s right wind is shown in Fig. 9. The test ship makes slow astern operation while proceeding at 4 knots. Although the time history of ship's heading after reducing her headway indicates some discrepancy between simulation and actual measurement, the predicted

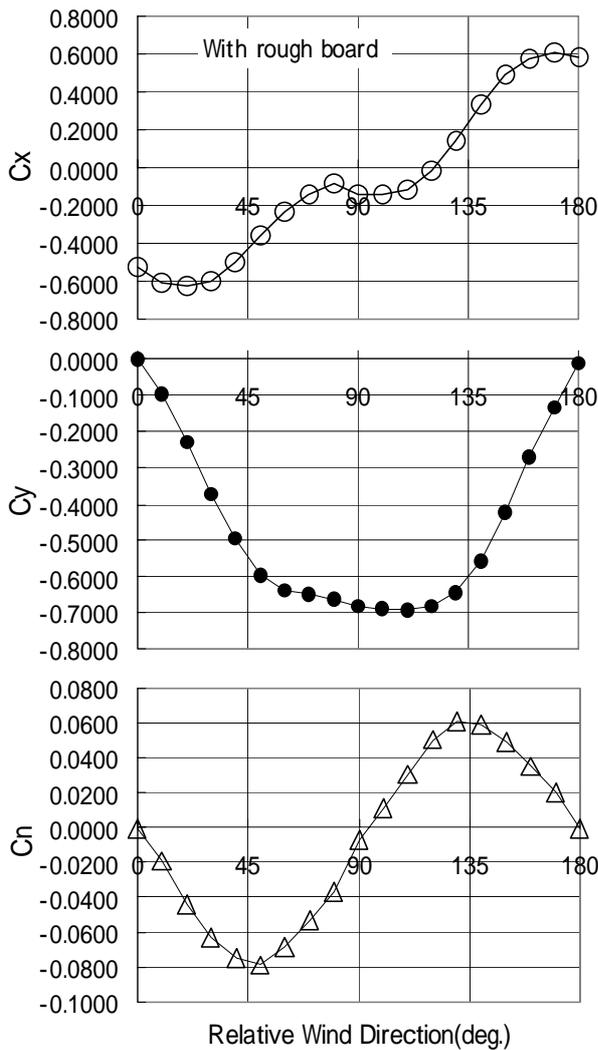


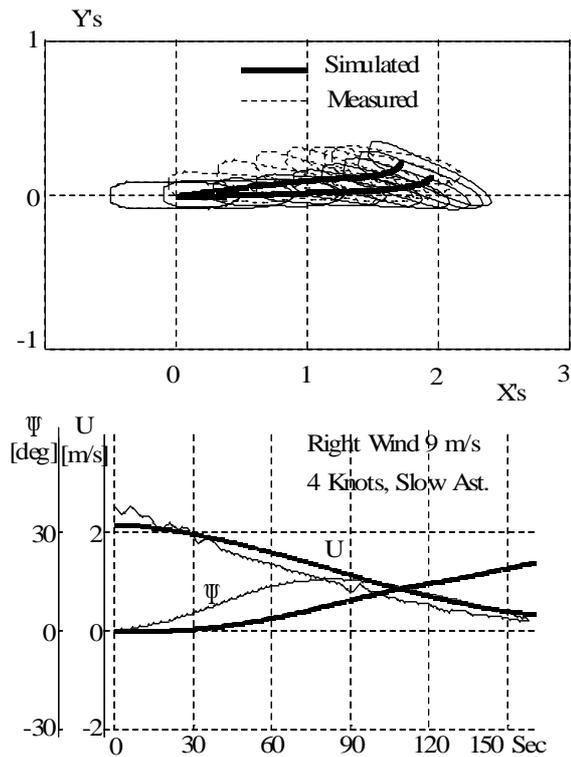
Fig.8 Wind force and moment coefficients

changes of ship speed and trajectory are in good agreement with the measured results. Thus, it seems reasonable to consider that the proposed simulation model represents the stopping motion accurately.

4. STOPPING MOTION OF CPP SHIPS AND THEIR EFFECTIVE MANEUVERING UNDER WINDY CONDITION

4.1 Critical range of stopping maneuver without tug assistance

In the stopping maneuver for berthing of a ship with a single CPP and single rudder, shiphandlers reduce her speed to the minimum steerage way beforehand and apply a weak reversing operation such as slow astern. The stopping motion of the test ship can be simulated for various wind force and wind direction using the mathematical model described in the previous section. Fig. 10 shows the simulation results of the stopping maneuver where the propeller was put slow astern



while proceeding at 3 knots. Head reach

Fig. 9 Comparison of stopping motion between measured and simulated (Beam wind)

($X'_s = X_s / L$), Side reach ($Y'_s = Y_s / B$) and Head turning angle (Ψ) are plotted in the figure against relative wind direction.

The simulation results shows that the ship always turns her head into the wind during stopping maneuver and the head turning angle increases in proportion to the wind force. The head turning angle in the quarter wind is greater than that in the starboard bow wind or port bow wind. In case of the strong quarter wind, the head turning angle becomes greater according to the change of relative wind direction to the aft. When wind direction changes to the opposite side in the follow wind, the ship makes significant head turning motion into the wind. On the side reach, the ship is forced to drift leeward considerably under strong beam wind or quarter wind conditions. Since the obtained results agree with the same simulation results using PCC [4] qualitatively, these characteristics seem to be common in ships with large lateral area above water line.

When berthing a ship to the pier without tug assistance, assuming that the ship has a right turning single propeller, the ship approaches at 15 to 20 degree angle to the berth and stops at the front of berth approximately $1.5B$ off in parallel to the berth. It is assumed that the stopping maneuver under windy condition can be made without tug assistance in the range of $Y'_s / B = \pm 1.5$ and $\Psi = \pm 20^\circ$. Therefore, the authors consider that the range of wind direction

and its force in which the ship is difficult to make stopping maneuver without tug assistance can be predicted using the simulation results shown in Fig. 10 under the above assumption. The dotted area on the figure indicates this critical range for the ship and it can be predicted that she needs tug assistance during stopping maneuver when she is confronted with the wind above 10 m/s in the range of starboard bow to quarter and port bow to quarter.

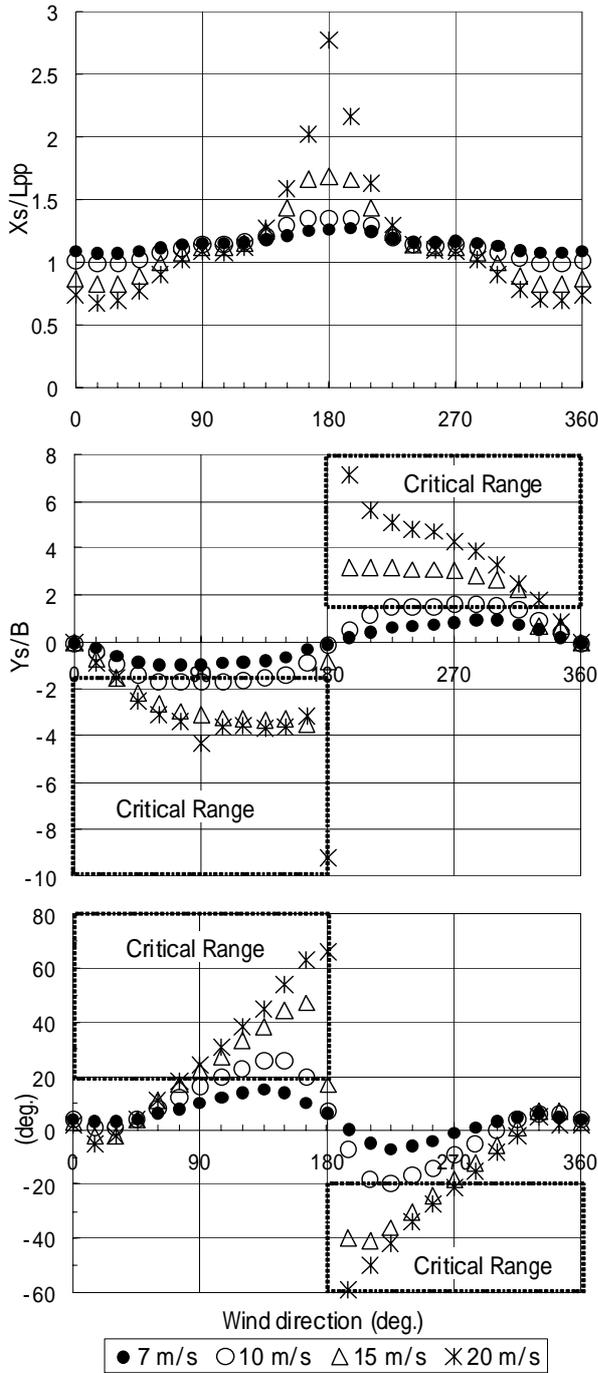


Fig. 10 Stopping ability and critical range of stopping maneuver under windy condition (3 knots to slow astern)

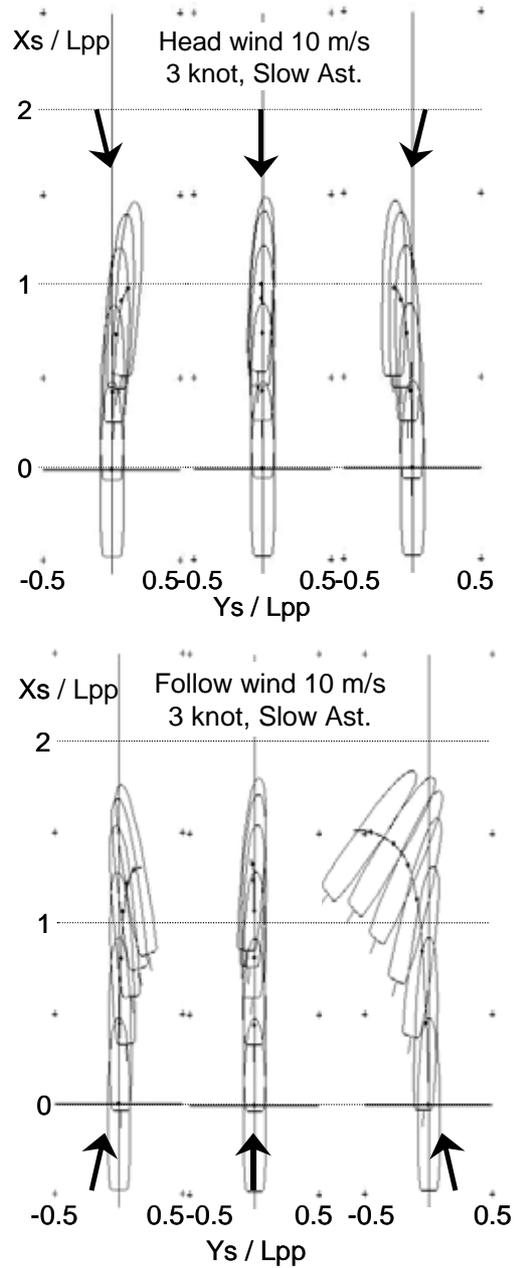


Fig. 11 Comparison of trajectories between in the head wind and in the follow wind

4.2 Proposal of effective stopping maneuver

From the simulation results shown in Fig. 10, it can be inferred that stopping maneuver without tug assistance is feasible both in the head wind and the follow wind. These results seem to indicate the advantage of typical stopping maneuver that set the approaching course toward the berth into the wind or before the wind. However a large difference is observed in the size of turning motion between the stopping maneuver in the head wind and that in the follow wind. Fig. 11 shows the comparison of trajectories in the head wind and those in the follow wind.

In case of the head wind, when the wind direction

changes 2 points (22.5 degrees) leftward or rightward from the right ahead, little difference is observed in each of trajectories. On the other hand, in case of the follow wind, if the wind direction changes 2 points leftward or rightward from the right aft., the ship turns her head windward significantly and makes different stopping motion.

It is well known that the stopping motion is fixed by the apparent advance constant $J_{s0} = U_0 / (n \cdot p)$ at the initial stage of propeller reversing [5] and the motion increases in proportion to $|J_{s0}|$ as describes in section 2. Therefore, the size of stopping motion can be reduced by maneuvering so that $|J_{s0}|$ becomes smaller. The authors propose an effective maneuver that applies a little higher propeller reversing than in a normal stopping operation in order to reduce the size of turning motion in the follow wind. Fig. 12 shows the simulation results of the proposed stopping maneuver. The ship makes almost the same stopping motion as those in the head wind (Fig. 11) by applying the half astern operation in the follow wind.

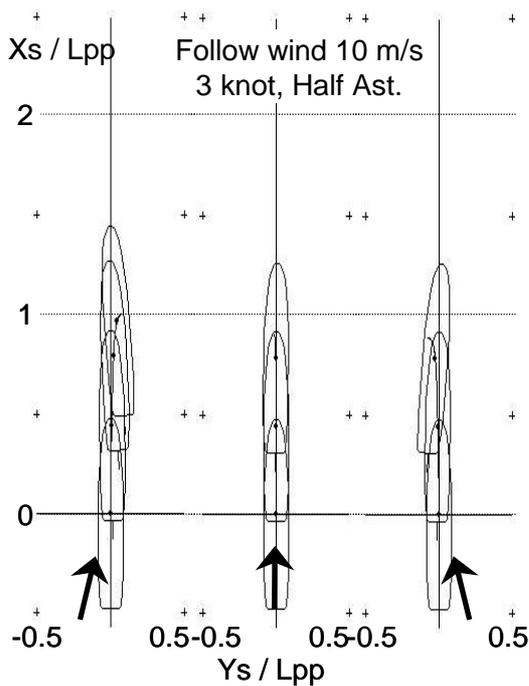


Fig. 12 Effective stopping maneuver in the follow wind

5. CONCLUSION

The authors performed a full scale experiment and a simulation study in order to investigate the turning motion during stopping maneuver of a ship with a single CPP and single rudder and proposed an effective stopping maneuver of CPP ships under windy condition. Results obtained in this study are summarized as follows.

- (1) In case of the tested ship, the turning motion during stopping maneuver is found less stable with a CPP than with a FPP. It seems that there are some differences in the hydrodynamic forces between CPP and FPP on propeller reversing. For the investigation of the hydrodynamic force, further model tests of CPP are desired.
- (2) In a CPP ship, the direction of turning motion during stopping maneuver can be determined by the relative wind direction.
- (3) As CPP ships are forced to drift leeward and turn their heads windward significantly during the stopping maneuver under beam or quarter wind conditions, it is recommended to set the approaching course toward the berth into the wind or before the wind.
- (4) When wind direction changes to the opposite side during a stopping maneuver in the strong follow wind, the ship turns her head windward significantly. Even in such case, the size of this turning motion can be sufficiently reduced by applying a little higher propeller reversing than the normal stopping maneuver.
- (5) The critical range of a stopping maneuver without tug assistance under windy condition can be estimated by the proposed simulation procedure.

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