2006년도 해양환경안전학회 추계학술발표회

論 文

The assessment of Safe Navigation Regarding Hydrodynamic forces between ships in Restricted Waterways

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ABSTRACT : *This paper is primarily focused on the safe navigation between overtaking and overtaken vesselsin restricted waterways under the external forces, such as wind and current. The maneuvering simulation between two ships was conducted to find an appropriate safe speed and distance, which is required to avoid collision. From the viewpoint of marine safety, a greater transversedistance between two ships is more needed for the smaller vessel. Regardless of external forces, the smaller vessel will get a greater effect of hydrodynamic forces than the bigger one. In the case of close navigation between ships under the forces of wind and current, the vessel moving at a lower speed is potentially hazardous because the rudder force of the lower speed vessel is not sufficient for steady-state course-keeping, compared to that of the higher speed vessel.*

KEY WORDS : Ship handling, Safe navigation, Restricted waterways, Overtaking and overtaken vessel, Ship-speed ratios, Hydrodynamic forces, Transverse and longitudinal distance

1. Introduction

From the technical viewpoint, vessels are continuously enlarged in size and greatly specialized in structure for the cargo spaces and dramatically automatized in navigating, cargo operating and various other operations, which require highertechniques in operating the vessels. However, in spite of great development in modern techniques of shipbuilding, many sea accidents of large vessels in confined waters have been occurring successively. Considering these accidents, problems of ship handling in confined waters have been receiving a great deal of attention in recent years. Also, the problem of ship controllability in confined waters due to the effect of shallow water or inherently restricted nature of waterways is the main concern not only of naval architects and ship operators but also of engineers who will design future waterways. Therefore, the maneuvering motion accompanied with the hydrodynamic forces between vessels moving each other in close proximity in a harbour or in a narrow channel has been of considerable interest. Accordingly, the safe operation and effective control of the vessel require a good understanding of the hydrodynamic forces that will encounter. In particular, for the specific case of overtaking between ships in restricted waterways, the situation is get more complex by the external forces, such as wind ,current, restricted maneuvering boundaries, and interaction effects of ships. So, it is extremely important that the ship operator should be able to maintain full control of the ship. For this to be possible, the hydrodynamic forces between ships in restricted waterways should be properly understood, and the works on this part have been reported for the past years. Yeung et al. (1980) analyzed hydrodynamic interactions of a slow-moving vessel with a coastline or an obstacle in shallow water using slender-body theory. In this paper, the assumptions of the theory are that the fluid is inviscid and the flow irrotational except for a thin vortex sheet behind the vessel. Similar works were also reported by Yoon(1982, 1986). Kijima et al.(1991) studied on the interaction effects between two ships in the proximity of bank wall. Yasukawa(1991) investigatedon the bank effect of ship maneuverability in a channel with varying width. Despite those past investigations, more detailed knowledge on maneuvering characteristic for the safe navigation between ships in restricted waterways isstill being required to prevent marine disasters.

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2. Formulation

The coordinate system fixed on each ship is shown by $o_i - x_i y_i (i=1,2)$ in Fig.1. Consider two vessels designated as ship 1 and ship 2 moving at speed $U_i(i=1,2)$ in an inviscid fluid of depth h. In this case, each ship is assumed to move each other in a straight line through calm water of uniform depth h. S_{P12} and S_{T12} are lateral and longitudinal distances between ship 1 and ship 2 in Fig.1. Assuming small Froude number, the free surface is assumed to be rigid wall, which implies that the effects of waves are neglected. Then, double body models of the two ships can be considered. The velocity potential $\phi(x,y,z;t)$, which expresses the disturbance generated by the motion of the ships, should satisfy the following conditions:

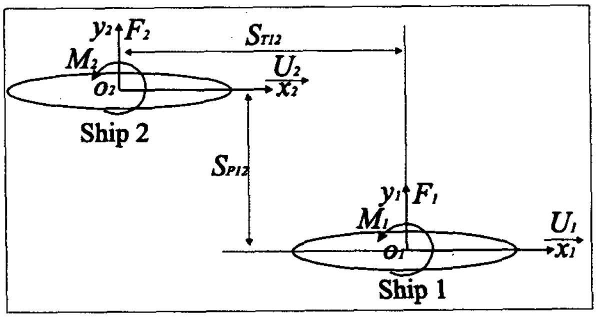

Fig.1 Coordinate system

$$\nabla^2\phi(x,y,z;t)=0 \quad \text{--(1)}$$

$$\left|\frac{\partial\phi}{\partial z}\right|_{z=\pm h}=0 \quad \text{---(2)}$$

$$\left|\frac{\partial\phi}{\partial n_i}\right|_{B_i}=U_i(t)(n_x)_i \quad \text{--(3)}$$

$$\phi \to 0 \;\; at \;\; \sqrt{x_i^2+y_i^2+z_i^2} \to \infty \quad \text{------------------(4)}$$

where B_i is the body surface of ship i. $(n_x)_i$ is the x_i component of the unit normal $\vec{n}$ interior to B_i. The following assumptions of slenderness parameter ε are made to simplify the problem.

$$L_i=o(1),\;\; B_i=o(\varepsilon),\;\; d_i=o(\varepsilon)(i=1,2)$$
$$h=o(\varepsilon),\;\; S_{P12}=o(1)$$

Under these assumptions, the problem can be treated as two-dimensional in the inner and outer region.

2. 1 Inner and Outer solution

The velocity potential $\Phi_i\ (i=1,2)$ in the inner region can be replaced by the velocity potential representing two-dimensional problems of a ship cross section between parallel walls representing the bottom and its mirror image above the water surface. Then, Φ_i can be expressed as follows (Kijima et al. 1991):

$$\Phi_i(y_i,z_i;x_i;t)=U_i(t)\Phi_i^{(1)}(y_i,z_i) + V_i^*(x_i,t)\Phi_i^{(2)}(y_i,z_i)+f_i(x_i,t) \quad \text{-------------(5)}$$

where, $\Phi_i^{(1)}$ and $\Phi_i^{(2)}$ are unit velocity potentials for longitudinal and lateral motion, V_i^* represents the cross-flow velocity at $\sum_i(x_i)$, and f_i is a term being constant in each cross-section plane, which is necessary to match the inner and outer region.

In the meantime, the velocity potential ϕ_i in the outer region is represented by distributing sources and vortices along the body axis (Kijima et al. 1991):

$$\phi_i(x,y;t)= \sum_{j=1}^{2}\frac{1}{2\pi}\{\int_{L_j}\sigma_j(s_j,t)\log\sqrt{(x-\xi)^2+(y-\eta)^2}ds_j + \int_{L_j w_j}\gamma_j(s_j,t)\tan^{-1}\left(\frac{y-\eta}{x-\xi}\right)ds_j\} \quad \text{----------(6)}$$

where $\sigma_j(s_j,t)$ and $\gamma_j(s_j,t)$ are the source and vortex strengths, respectively. L_j and w_j denote the integration along ship j and vortex wake shed behind the ship j, respectively. ξ and η represent the source and vortex point.

2.2 Matching and hydrodynamic force and moment

Where the inner and outer region overlap, the velocity potential Φ_i and ϕ_i should correspond to each other. By matching terms of Φ_i and ϕ_i that have similar nature, the following integral equation for γ_i can be obtained as follows(Kijima et al. 1991):

$$\frac{1}{2C_i(x_i)}\int_{x_i}^{\frac{L_i}{2}}\gamma_i(\xi_i,t)d\xi_i-\frac{1}{2\pi}\int_{L_iw_i}\gamma_i(s_i,t)\left\{\frac{1}{x_i-\xi_i}\right\}ds_i$$
$$-\sum_{j=1,j\neq i}^{2}\frac{1}{2\pi}\int_{L_jw_j}\gamma_j(s_j,t)\frac{\partial G_j^{(\gamma)}}{\partial y_i}(x_0,y_0;\xi,\eta)ds_j$$
$$=\sum_{j=1,j\neq i}^{2}\frac{1}{2\pi}\int_{L_j}\sigma_j(s_j,t)\frac{\partial G_j^{(\sigma)}}{\partial y_i}(x_0,y_0;\xi,\eta)ds_j$$
$$\text{-----}(7)$$

The hydrodynamic forces acting on ships can be obtained by solving this integral equation for γ_i. The solution γ_i of equation (7) should satisfy the additional conditions:

$$\gamma_i(x_i,t)=\gamma_i(x_i)\quad for\ x_i \prec -\frac{L_i}{2},$$
$$\int_{-\infty}^{\frac{L_i}{2}}\gamma_i(\xi_i,t)d\xi_i=0,\quad \gamma_i(x_i=-\frac{L_i}{2},t)=-\frac{1}{U_i}\frac{d\Gamma_i}{dt}$$
$$\text{----------}(8)$$

where Γ_i is the bound circulation of ship i. The lateral force and yawing moment acting on ship i can be obtained as follows:

$$F_i(t)=-h_i\int_{-\frac{L_i}{2}}^{\frac{L_i}{2}}\Delta P(x_i,t)dx_i$$
$$M_i(t)=-h_i\int_{-\frac{L_i}{2}}^{\frac{L_i}{2}}x_i\Delta P(x_i,t)dx_i$$
$$\text{---------------------------}(9)$$

where Δp is the difference of linearized pressure about x_i-axis and non-dimensional expression for the lateral force, C_{Fi}, and yawing moment, C_{Mi}, affecting upon two vessels is given by

$$C_{Fi}=\frac{F_i}{\frac{1}{2}\rho L_i d_i U_i^2}\ ,\quad C_{Mi}=\frac{M_i}{\frac{1}{2}\rho L_i^2 d_i U_i^2}$$
$$\text{---------------}(10)$$

where, L_i is the ship length of ship i and d_i is the draft of ship i. ρ is the water density.

3. Prediction of hydrodynamic forces between two ships

In this section, the hydrodynamic forces acting on two ships while overtaking in shallow waters have been examined. A parametric study on the numerical calculationshas been conducted on the general cargo ship as shown in Table 1 and Table 2, which both ship 1 and ship 2 are always similar form. A typical overtaking condition was investigated as shown in Fig.1. Provided that the speed of a ship 1 (denoted as U_1) is maintained at 10 kt, the velocities of overtaking or overtaken ship 2 (denoted as U_2) were varied, such as 6 kt, 12kt and 15kt, respectively. The ratios of ship length selected for comparison were 0.5, 1.0 and 1.18.

Table. 1. Principal particulars

L (m)	155
B (m)	26
d (m)	8.7
C_B	0.6978

Table. 2. Types with parameters L_2/L_1 and U_2/U_1

Types	Ratio between ships		
	L_2/L_1	U_2/U_1	
Type 1	0.5	0.6, 1.2, 1.5	
Type 2	1.0	0.6, 1.2, 1.5	
Type 3	1.18	0.6, 1.2, 1.5	

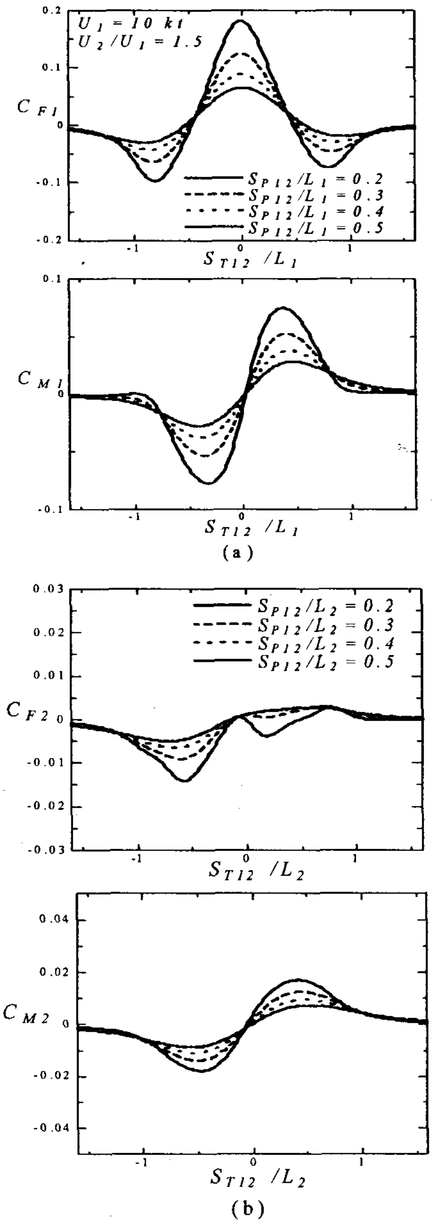

Fig.2. Lateral force and yawing moment coefficients acting on ship 1 and ship 2

Fig. 2 shows the result for the interaction forces with a function of the lateral distance between two ships for the case of 1.5 in U_2/U_1. The separation between two ships was chosen to be 0.2 to 0.5 times of a ship length under the condition of 1.0 in L_2/L_1. Fig. 2(a) and (b) show the result for ship 1 and ship 2, respectively. From this figure, the overtaken and overtaking vessel experience an attracting force which increases as two vesselsapproach each other. When the bow of overtaking vessel approaches the stern of the overtaken vessel, the two ships encounter the first hump of the attracting force and a maximum bow-in moment. The maximum repulsive force value is achieved when the midship of overtaking vessel passes the one of overtaken vessel. Then the sway force reverses to attain the steady motion due to the sufficient longitudinal distance between two ships. Two ships experience the maximum bow-out moment when the longitudinal distance between the midship of two ships is about 0.5 times of a ship length in distance, then the bow-out moment acting on two vessels due to the sufficient longitudinal distance between two ships disappears. For hydrodynamic forces, the effect of ship 1 is quantitatively bigger than the one of ship 2.

3.1 Simulation of ship manoeuvring motion under the external forces

In the meantime, the mathematical model of ship manoeuvring motion under the condition of current and wind can be expressed as follows(Kijima, 1990):

$$(m_i' + m_{xi}')\left(\frac{L_i}{U_i}\right)\left(\frac{\dot{U}_i}{U_i}\cos\beta_i - \dot{\beta}_i\sin\beta_i\right) + (m_i' + m_{yi}')r_i'\sin\beta_i' - (m_{xi}' - m_{yi}')\frac{V_{ci}}{U_i}r_i'\sin(\psi_i' - \alpha) = X_{Hi}' + X_{Pi}' + X_{Ri}' + X_{Wi}' \quad \text{-----(20)}$$

$$-(m_i' + m_{yi}')\left(\frac{L_i}{U_i}\right)\left(\frac{\dot{U}_i}{U_i}\sin\beta_i - \dot{\beta}_i\cos\beta_i\right) + (m_i' + m_{xi}')r_i'\cos\beta_i' - (m_{yi}' - m_{xi}')\frac{V_{ci}}{U_i}r_i'\cos(\psi_i' - \alpha) = Y_{Hi}' + Y_{Ri}' + Y_{Ii}' + Y_{Wi}' \quad \text{---(21)}$$

$$(I_{zzi}' + i_{zzi}')\left(\frac{L_i}{U_i}\right)^2\left(\frac{\dot{U}_i}{L_i}r_i' + \frac{U_i}{L_i}\dot{r}_i'\right) = N_{Hi}' + N_{Ri}' + N_{Ii}' + N_{Wi}' \quad \text{-----------------------(22)}$$

where, m_i' represents non-dimensionalized mass of ship i, m_{xi}' and m_{yi}' represent x, y axis components of non-dimensionalized added mass of ship i, β_i means drift angle of ship i, respectively. The subscript H,P,R,I and W mean ship hull, propeller, rudder, component of the hydrodynamic interaction forces between two ships and wind, and also V_c,α,ψ_i mean current velocity, current direction and heading angle of ship i. X,Y and N represent the external force of x,y axis and yaw moment about the center of gravity of the ship. Wind forces and moments acting on ships were estimated by Fujiwara et al. (1998). A rudder angle is controlled to keep course as follows:

$$\delta_i = \delta_{0i} - K_1(\psi_i - \psi_{0i}) - K_2 r_i' \qquad (23)$$

where δ_i, r_i' represent rudder angle, non-dimensional angular velocity of ship i. Subscript '0' indicates initial values and also, K_1 and K_2 represent the control gain constants.

4. Results and discussion

In this section, the ship maneuvering motions under the current and wind are simulated numerically using the predicted hydrodynamic interaction forces between ships while overtaking in shallow waters. Fig.3 shows the result of ship maneuvering simulation with function of the external force and U_2/U_1. In this case, the wind velocity (V_W), current velocity(V_c), wind direction(ν)and current direction (α) were taken as 10m/s, 4kt, 120° and 0°, respectively. However, the U_2/U_1 was taken as 0.6, 1.2 and 1.5. The separation between two ships, S_{P12}, was taken as 0.3 times of ship 1 and L_2/L_1 was taken as 1.0 in $h/d_1 = 1.2$. The control gain constants used in these numerical simulations are $K_1 = K_2 = 5.0$, and maximum rudder angle, $\delta_{max} = 10°$.

When and if one ship passes the other ship, any yawing moments of the overtaken vessel as shown in Fig.3show strong motion due to the hydrodynamic forces between ships. Then once initiated such a turn would develop rapidly, the rudder force of the overtaken vessel under the condition of $\delta_{max} = 10°$ was not large enough to stop this tendency. In case of 1.2 in U_2/U_1 (Fig.3(b)), there was a most clear tendency for the overtaken vessel to deviate to starboard, compared to the case of 1.5 in U_2/U_1 (Fig.3(c)). In the meantime, in case of 0.6 in U_2/U_1 (Fig.3(a)), the maneuvering for the vessel moving at a lower speed with ranges of 10 degrees in rudder angle was impossible. It is indicated that the rudder force of vessel moving at a lower speed is not sufficient to control hydrodynamic forces between ships.

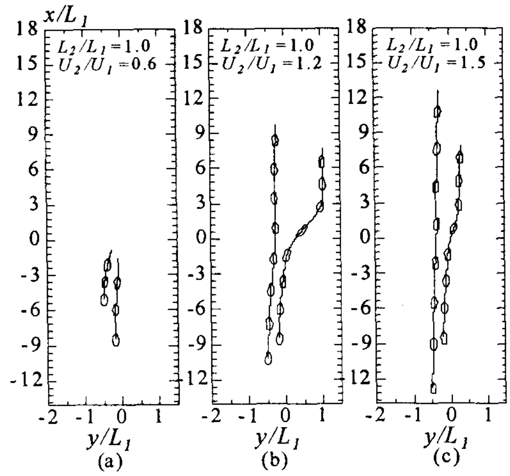

Fig.3. Ship trajectories under the external forces with rudder control

Fig. 4 shows the result for deviated maximum lateral distance from the original course with function of the external forces for the case of 1.2 in U_2/U_1. The separation between two ships was chosen to be 0.4 to 0.7 times of L_1 under the condition of 1.0 in L_2/L_1. The control gain constants used in these numerical simulations are $K_1 = K_2 = 5.0$ and $\delta_{max} = 10°$. In Fig. 4, I, W, C represent hydrodynamic force between two ships, wind and current. Fig. 4(a) and (b) show the result for ship 1 and ship 2, respectively. As shown in Fig. 4, with no consideration of external forces, the courses of two ships are notalmost deviated from the original direction under the condition of $\delta_{max} = 10°$ even though the separation between ships is 0.4 times of L_1. In addition, considering the wind only as parameter, it indicated that two ships can beunharmed maintaining its own original course. However, an overtaken vessel is much deviated from the original course if both wind and current are considered, while it is guided securely with intended direction for the overtaking vessel. On the other hand, if the lateral distance between two ships is about 0.6 times of L_1, an overtaken vessel is not much deviated from the original course under the current and wind.

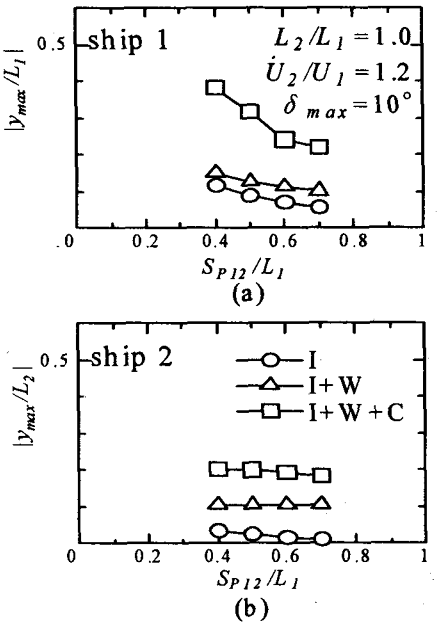

Fig.4.Deviated maximum lateral distance from the original course with function of the external forces

Fig. 5 displays the result for deviated maximum lateral distance from the original course with function of the S_{P12}/L_1 for the case of 1.5 in U_2/U_1. The separation between two ships was chosen to be 0.3 to 0.6 times of L_1 under the condition of 1.0 in L_2/L_1. From Figs. 5 and 6, it showed that transverse axis signifies the rudder angle needed to control external forces while sustaining original course, and vertical axis is defined as the non-dimensionalized deviated maximumlateral distance from the original course. From Fig. 5, an overtaken and overtaking vessel's courses are not largely deviated from the original direction under the condition of $\delta_{max}=15°$ even though the separation between two ships is 0.3 times of L_1. Also, if the lateral distance between two ships is about 0.5 times of L_1, an overtaking and overtaken vessel is not pretty much deviated from the original course under the condition of $\delta_{max}=10°$.

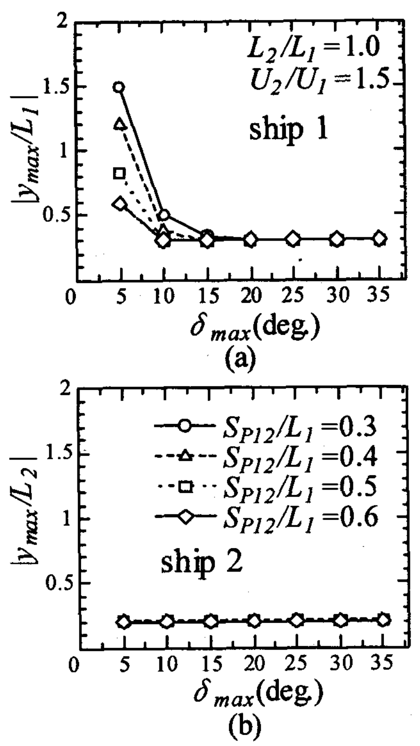

Fig.5 Deviated maximum lateral distance from the original course with function of S_{P12}

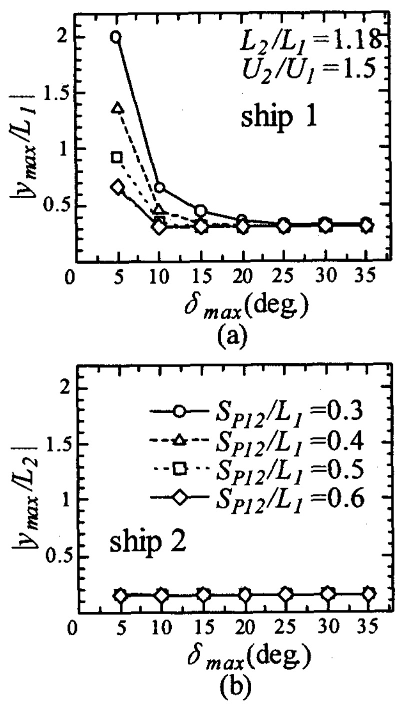

Fig.6.Deviated maximum lateral distance from the original course with function of S_{P12}

The deviated maximum lateral distance from the original course with function of the S_{P12} for the case of 1.5 in U_2/U_1 is shown in Fig. 6. The separation between two ships was chosen to be 0.3 to 0.6 times of L_1 under the condition of 1.18 in L_2/L_1. From Fig. 6, if the lateral distance between two ships is about 0.5 times of L_1, an overtaking and overtaken vessel is not pretty much deviated from the original course under the condition of $\delta_{max} = 10^\circ$.

5. Conclusion

From the simulation of ship manoeuvring motions on the safe navigation between ships while overtaking in shallow waters under the current and wind, the following conclusions can be drawn.

Under the same condition, the lateral distance between ships on a safe navigation is more required for the velocity ratio of 1.2, compared to the cases of 0.6 and 1.5.

In case of close navigation, the smaller vessel will get a greater effect of interaction forces than the bigger vessel.

In case of proximal navigation under the wind and current, the low-speed vessel is potentially hazardous because the rudder force of low-speed vessel needed for steady-state course-keeping is not sufficient, comparing with the high-speed vessel.

For the velocity ratio of U2/U1=0.6, manoeuvring for the low-speed vessel with ranges of 10 degrees in rudder angle was impossible.

Under the condition of U2/U1=0.6, the deviation for the low-speed vessel even with rudder angle of 25 degrees was comparatively larger from its intended course, and high-caution for the safety is needed.

In case of proximal navigation under the wind and current, the lateral distance between ships, rudder angle, and ship speed had a critical influence on a safe navigation.

As a result, from the viewpoint of safe navigation, when one vessel tries to overtake the other vessel with small rudder angle, the high-caution is more needed and the increase of velocity for those vessels running at low-speed is demanded.

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