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Hydrodynamic Forces between Vessels and Safe Maneuvering under Wind-Effect in Confined Waters

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Abstract

It is well known that the ship maneuvering motion is greatly affected by hydrodynamic forces and moments acting between two ships passing too close to each other in confined waters, such as in a harbor or narrow channel. This hydrodynamic forces and moments can be assumed to be the functions of the longitudinal and transverse distance along with their speeds. The aim of the present research is to develop a guideline of ship velocity and safe distance between ships to avoid the influence of the hydrodynamic forces and moments and to navigate ships safely in confined waters. From the perspective of marine safety, considering the interaction and wind effect as a parameter, an overtaking and overtaken vessel navigating too close to each other under the condition of wind direction from 80^o to 150^o should be cautioned with high alert, regardless of ship types. Also, regardless of the ship-velocity ratio and ship types, an overtaking and overtaken vessel can be maneuvered safely without deviating from the original course under the following conditions; the transverse distance between two vessels is approximately kept at 1.0 times of ship length and 5 through 10 degrees of range in maximum rudder angle.

Keywords: Ship maneuvering motion, Safe navigation, Hydrodynamic force, Longitudinal and transverse distance, Confined waters, Wind effect

1. Introduction

When two vessels are navigating within a certain proximity to each other, the resulting hydrodynamic forces can cause significant loads to be exerted on one or all of the vessels. Such loads are important in a confined channel or in a canal, where the restricted flow accentuates the interaction effects and where the vessels are more likely to be close due to navigational constraints. In particular, the situation for the specific case of overtaking between vessels in confined waters under the effect of wind is made more complex by wind, restricted maneuvering boundaries, and the interaction effects of ships on each other. So, it is extremely important that the ship operator should be able to maintain full control of the ship during operations. For this to be possible, the hydrodynamic forces between vessels in confined waters such as in a harbor or in a narrow channel should be properly understood, and the works on this part have been reported for the past years. Yeung et al. (1980) studied hydrodynamic forces 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 reported by Yoon(1982, 1986), Davis(1986), Landweber et al. (1991). Kijima et al.(1991) studied on the interaction effects between

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two ships in the proximity of a bank wall. Yasukawa (1991) investigated the bank effect of ship maneuverability in a channel with varying width. Also, Korsmeyer et al.(1993) analyzed the theory and computation for the interaction forces among multiple ships or bodies which are operating near to each other. Despite the past investigations, the detailed knowledge on maneuvering characteristic for the safe navigation between vessels in confined waters is still being required to prevent further marine disasters.

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 at each other in a straight line through calm water of uniform depth h. S_{P12} and S_{T12} are transverse and longitudinal distance between vessels in Fig. 1. Also, V_W , v mean the wind velocity and wind direction. 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:

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

$$\left| \frac{\partial \phi}{\partial z} \right|_{z=\pm h} = 0 \tag{2}$$

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

$$\phi \to 0 \quad at \quad \sqrt{x_i^2 + y_i^2 + z_i^2} \quad \to \infty \tag{4}$$

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.

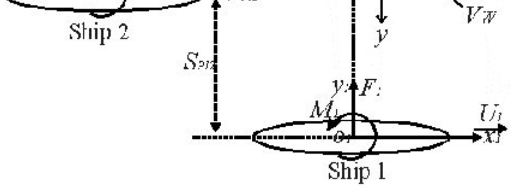


Fig. 1. Coordinate system.

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

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 Φ_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):

$$\begin{aligned} \Phi_i(y_i,z_i;x_i;t) &= U_i(t)\Phi_i^{(1)}(y_i,z_i) \\ &\quad + V_i^*(x_i,t)\Phi_i^{(2)}(y_i,z_i) + f_i(x_i,t) \end{aligned} \tag{5}$$

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):

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

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):

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

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

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

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:

$$\begin{aligned}&F_i(t)=-h_i\int_{-\frac{L_i}{2}}^{\frac{L_i}{2}}\Delta P(x_i,t)dx_i\\&M_i(t)=-h_i\int_{-\frac{L_i}{2}}^{\frac{L_i}{2}}x_i\Delta P(x_i,t)dx_i\end{aligned}\tag{9}$$

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

$$C_{Fi}=\frac{F_i}{\frac{1}{2}\rho L_i d_i U_i^2}\ ,\ C_{Mi}=\frac{M_i}{\frac{1}{2}\rho L_i^2 d_i U_i^2}\tag{10}$$

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 vessels

In this section, the hydrodynamic forces acting on two vessels while overtaking in shallow waters have been examined. A parametric study on the numerical calculations has been conducted on four different ship types as shown in Table 1. A typical overtaking condition was investigated as shown in Fig. 1. Provided that the speed of 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 ratio of ship length selected for comparison was 1.0 as shown in Table 2.

Table 1. Principal particulars.

	Cargo	Container	PCC	VLCC
L (m)	155.0	175.0	190.0	325.0
B (m)	26.0	25.375	32.26	53.0
d (m)	8.7	9.502	10.0	22.05
C_B	0.6978	0.5717	0.6178	0.830

Table 2. Types with parameters $L2/L1$ and $U2/U1$.

	Ratio between two vessels	
	$L2/L1$	$U2/U1$
Type	1.0	0.6, 1.2, 1.5

Figure 2 displays the computed hydrodynamic forces between two vessels with four different ship types for the case of 1.5 in U_2/U_1. The separation between two ships was chosen to be 0.2 times of a ship length under the condition of 1.0 in L_2/L_1. The solid lines show the result of hydrodynamic forces for the case of tanker. The dashed lines mean the result for the case of PCC, and the dotted lines show the result for the case of container. The dash dot lines mean the result for the case of general cargo ship. Figure 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 vessels approach 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 1.0 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 regardless of the ship types.

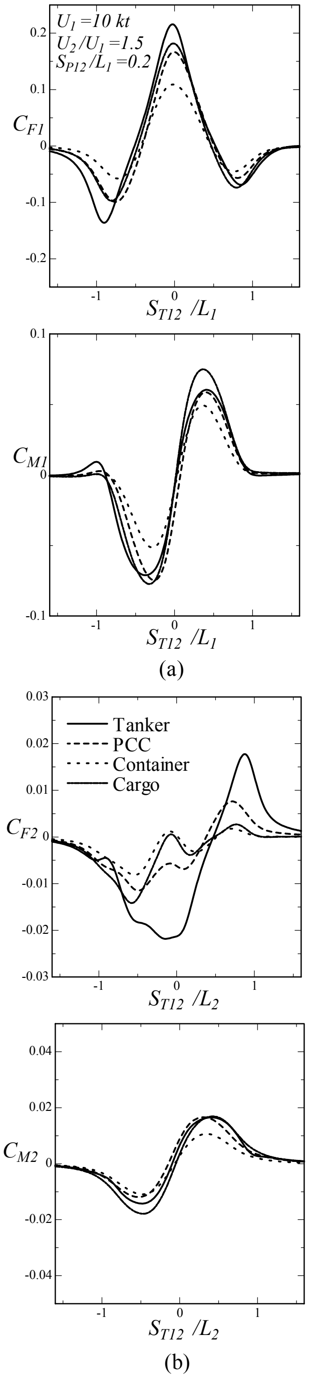


Fig. 2. Computed hydrodynamic forces acting on four different ship types.

3.1 Simulation of ship manoeuvring motion under the wind force

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

$$(m_i' + m_{xi}')\left(\frac{L_i}{U_i}\right)\left(\frac{\dot{U}_i}{U_i}\cos\beta_i - \dot{\beta}_i \sin\beta_i\right) \tag{11}$$
$$+(m_i' + m_{yi}')r_i'\sin\beta_i' = X_{Hi}' + X_{Pi}' + X_{Ri}' + X_{Wi}'$$

$$-(m_i' + m_{yi}')\left(\frac{L_i}{U_i}\right)\left(\frac{\dot{U}_i}{U_i}\sin\beta_i + \dot{\beta}_i \cos\beta_i\right) \tag{12}$$
$$+(m_i' + m_{xi}')r_i'\cos\beta_i' = Y_{Hi}' + Y_{Ri}' + Y_{Ii}' + Y_{Wi}'$$

$$(I_{zzi}' + i_{zzi}')\left(\frac{L_i}{U_i}\right)^2\left(\frac{\dot{U}_i}{L_i}r_i' + \frac{U_i}{L_i}\dot{r}_i'\right) \tag{13}$$
$$= N_{Hi}' + N_{Ri}' + N_{Ii}' + N_{Wi}'$$

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 interaction force between two ships and wind, and also ψ_i means 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:

$$\delta_i = \delta_{0i} - K_1(\psi_i - \psi_{0i}) - K_2 r_i' - K_3(S'_{Pi} - S'_{P0i}) \tag{14}$$

where δ_i, r_i' represent rudder angle, non-dimensional angular velocity of ship i, and also S'_{Pi} is non-dimensional predicted course. Subscript '0' indicates initial values and K_1, K_2, K_3 represent the control gain constants.

4. Results and discussion

In this section, the ship maneuvering motions under the wind are simulated numerically using the predicted hydrodynamic forces between vessels while overtaking in shallow waters.

Figure 3 shows the result for deviated maximum transverse distance from the original course with function of S_{P12} and U_2/U_1. From Fig. 3, it showed that S_{P12}/L_1 is defined as the non-dimensionalized transverse distance between vessels over ship-length, and $y_{\max}/L_1$ is signified as the non-dimensionalized deviated maximum lateral distance from the original course under 10 degrees in maximum rudder angle.

The lateral separation between two ships was chosen to be 0.3 to 1.0 times of L_1 under the condition of $\delta_{max} = 10^\circ$. The control gain constants used in these numerical simulations are $K_1 = K_2 = 5.0$, $K_3 = -1.0$. Ship type selected for comparison was VLCC. The effect of wind was not taken into account. From this figure, considering the interaction effect only as parameter, the effect of overtaken vessel is quantitatively bigger than the one of overtaking vessel regardless of the ship-velocity ratio. Also, from the perspective of marine safety, the transverse distance between ships is more needed for the ship-velocity ratio of 1.2, compared to the cases of 0.6 and 1.5.

Figure 4 shows the result of ship maneuvering simulation for comparison between interaction effect only as parameter and interaction and wind effect as parameter with function of wind direction. From Fig 4, as you may presume, solid line is the result for interaction- effect only to be considered, however, dotted line is a ship-trajectory for the case of both interaction and wind-effect to be concerned.

In this case, the wind velocity (V_W) was taken as 10m/s and wind direction(ν) were taken as 70°, 120°, 150^o, respectively. The separation between two ships, S_{P12}, was taken as 0.3 times of ship length and U_2/U_1 was taken as 1.2 in $h/d_1 = 1.2$. The control gain constants used in these numerical simulations are $K_1 = K_2 = 5.0, K_3 = -1.0$, and maximum rudder angle, $\delta_{\max} = 10^\circ$.

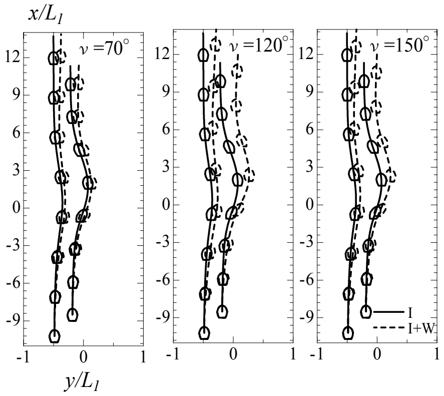
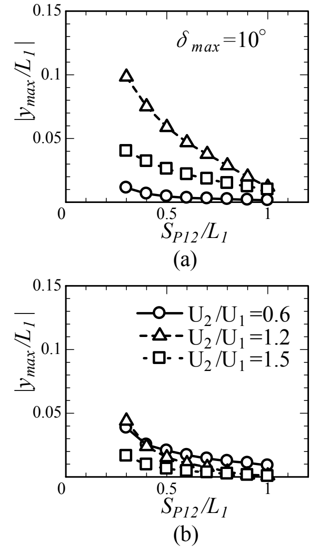


Fig. 4. Ship trajectories for comparison of interaction and wind effect.

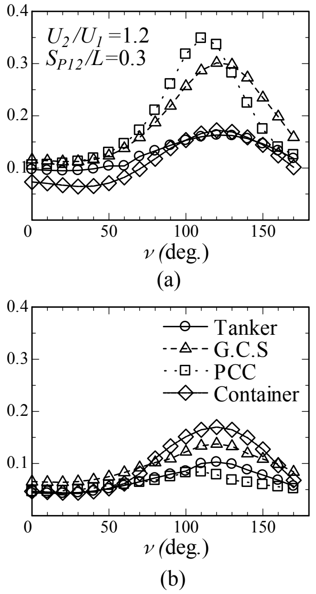
As shown in figure 4, if the interaction effect was the only factor to be considered, two vessels with maximum rudder angle of 10^o can navigate while keeping its original course even though the separation between ships is 0.3 times of ship length. In the



(a)

(b)

Fig. 3. Deviated maximum transverse distance from the original course with function of the U_2/U_1.



(a)

(b)

Fig. 5. Deviated maximum transverse distance from the original course with function of the wind effect.

meantime, when and if one ship passes the other ship, any yawing moments of the overtaken vessel as shown in Fig. 4 show some strong motion due to the wind force and hydrodynamic force between ships according to wind direction.

Figure 5 shows the result for deviated maximum transverse distance from the original course with function of the wind force and wind direction for the case of 1.2 in U_2/U_1. The separation between two ships was chosen to be 0.3 times of ship length under the condition of 1.0 in L_2/L_1. The control gain constants used in these numerical simulations are $K_1 = K_2 = 5.0, K_3 = -1.0$ and $\delta_{\max} = 10^{\circ}$. Figure 5(a) and (b) show the result for overtaking and overtaken vessel, respectively. From this figure, the external effect acting on the overtaken vessel is quantitatively bigger than the one of overtaking vessel regardless of the ship types. Also, the wind effect acting on the overtaking and overtaken vessel from 80^o to 150^o in wind direction is bigger than other wind direction.

5. Conclusion

From the simulation of ship maneuvering motions on the safe navigation while overtaking in shallow waters under the wind, the following conclusions can be drawn.

The hydrodynamic forces between vessels are predicted using calculation method based on the slender body theory. From the perspective of marine safety, considering the interaction and wind effect as a parameter, an overtaken PCC vessel navigating at a lower speed should be cautioned with high alert, and it is considered that speeding up an engine is required if necessary. Also, maximum lateral deviation of the overtaken vessel is arisen when the ratio of velocity of two vessels is 1.2 in the numerical simulation using two vessels that have the same particulars. However, if lateral distance between two vessels is larger than 1.0L, the lateral deviation with range of 10 degrees as a maximum rudder angle becomes smaller than 0.02L even though U_2/U_1 is 1.2. Eventually, regardless of the ship-velocity ratio and ship types, an overtaking and overtaken vessel can be maneuvered safely without deviating from the original course under the following conditions; the transverse distance between two vessels is approximately kept at 1.0 times of ship length and 5 through 10 degrees of range in maximum rudder angle.

Nomenclature

ε : Slenderness parameter

C_{Fi}, C_{Mi} : Dimensionless hydrodynamic force and yaw moment of ship i

K_1, K_2, K_3 : Control gain constant

L_i, B_i, d_i : Ship length, breadth, draught of ship i

m_i' : Non-dimensionalized mass of ship i

m_{xi}', m_{yi}' : x, y axis components of non-dimensionalized added mass of ship i

σ, γ : Source and vortex strength

S_{P12}, S_{T12} : Lateral and longitudinal distance between two ships,

ξ, η : Source and vortex point

S'_{Pi} : Non-dimensional predicted course

Δp : Difference of linearized pressure about x_i-axis

U_i : Ship velocity of ship i

$V_W, \ \nu, \ \psi_i, \beta_i$: Wind velocity, wind direction, heading angle, drift angle of ship i

X, Y and N : External force of x, y axis and yaw moment about center of gravity of ship

$\delta_i, \ r_i'$: Rudder angle and non-dimensional angular velocity of ship i

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