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A Study on the Minimum Safe Distance between Two Vessels in Confined Waters

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Abstract : *This paper is mainly concerned with the interaction effects between two vessels and sidewall with a mound. Experimental study on hydrodynamic forces between ship and sidewall with a mound was already shown in the previous paper, measured by varying the distances between ship and sidewall. The ship maneuvering simulation was conducted to find out the minimum safe distance between vessels, which is needed to avoid sea accident in confined waters. From the inspection of this investigation, it indicates the following result. When and if one vessel passes the other vessel through the proximity of sidewall with a mound, the spacing between two vessels is needed for the velocity ratio of 1.2, compared to the case of 1.5. Also, for the case of ship-size estimation, the ship maneuvering motion is more affected by interaction effects for the overtaken small vessel, compared to the overtaking large vessel.*

Key words : *Interaction effect, Maneuvering motion, Overtaking and overtaken vessel, Minimum safe distance, Sidewall, Confined waters*

1. Introduction

The maneuvering motion of a deep-drafted vessel due to the interaction effects between two large vessels and sidewall with a mound in confined waters, such as in a narrow channel, has been of considerable interest because the safe navigation and effective control of the large vessel require a good understanding of the interaction effects which it experiences. So, the proximal navigation of overtaking and overtaken large vessel or ship-bank interaction in confined waters have been important problems in channel design and ship operation in harbours, and the problems are complicated because of the shallow water effects as well as ships are navigating near bank or other ships. In the meantime, a large number of papers in this field have been reported on the interaction effects between ships or between ship and bank, and some improved results were obtained(Davis, 1986; Kijima et al., 1991; Lee, 2012, 2013; Norrbin, 1974; Newman, 1969; Yasukawa, 2002; Yeung et al., 1980). However, in case of close operation through the proximity of sidewall with a mound, there has been a lack of theoretical data on the safe distance between ships and sidewall with a mound affecting on the maneuvering motion in a narrow channel. Thus, the goal of this research is to propose the minimum safe distance between two ships to avoid marine disasters from the viewpoint of safe navigation in confined waters.

2. Theoretical Background

As shown in Fig. 1, the coordinate systems fixed on each ship and on the earth are shown by $o_i - x_i y_i$ (i =1,2) and $o - xy$ respectively. Consider two ships designated as ship 1 and ship 2 moving at speed U_i (i =1,2) in an inviscid fluid of depth h. S_{P12} and S_{T12} are lateral and longitudinal distance between two ships, and S_{P1} and S_{T1} are lateral and longitudinal distance between ship and sidewall with a mound. 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 $\phi(x,y,z;t)$,

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which express the disturbance generated by the motion of the ships, should satisfy the following conditions;

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

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

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

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

where, B_i is the body surface of ship i and $(n_x)_i$ 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(Kijima et al., 1987, 1991).

$$L = O(1)\ ,\ B = O(\epsilon)\ ,\ d = O(\epsilon)\ ,\ h = O(\epsilon)\ ,\ S_{P12} = O(1)\ \text{...}(5)$$

Under these assumptions, the problem can be treated as two-dimensional separately in the inner and outer region(Kijima et al., 1987, 1991).

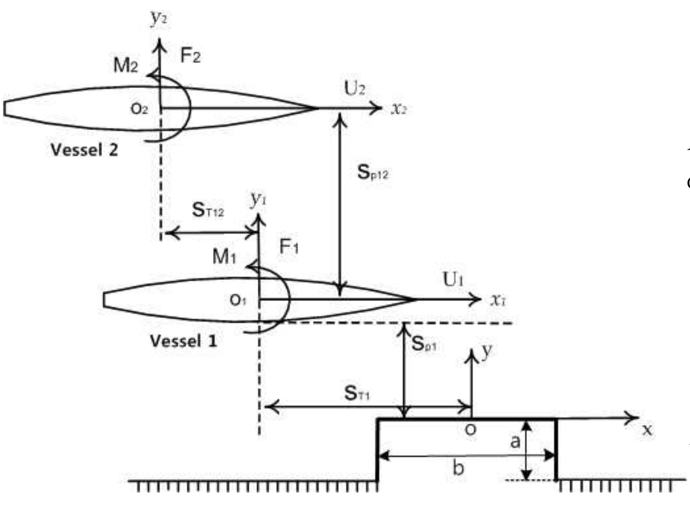

Fig. 1 Coordinate system

3. Simulation of ship maneuvering motion

In this section, the ship maneuvering motion is simulated numerically using the predicted and measured hydrodynamic forces. A parametric study on the numerical calculation has been conducted on the general cargo ship as shown in table 1 and table 2, which both of overtaken and overtaking vessel are always similar form. For the case of different ratio of 0.5(L_1=155m, L_2=77.5m), 1.0(L_1=155m, L_2=155m) and 1.18 (L_1=155m, L_2=182.9m) in L_2/L_1 and for the case of 0.6 (U_1=10kt, U_2=6kt), 1.2(U_1=10kt, U_2=12kt) and 1.5 (U_1=10kt, U_2=15kt) in U_2/U_1 as parameters, the hydrodynamic forces between two vessels in open sea have been computed. Also, in this study the external forces were not taken into account.

Table 1 Principle particulars

	General cargo vessel	
	Model	Full Scale
L (m)	2.5	155.0
B (m)	0.4194	26.0
d (m)	0.1403	8.70
C_B	0.6978	

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

Types	Ratio between two vessels		
	L_2/L_1		U_2/U_1
	L_1	L_2	
Type 2	155m	155m	1.2, 1.5
Type 3	155m	182.9m	1.2, 1.5

Also, the mathematical model for ship maneuvering motion can be expressed as follows:

$$(m_i' + m_{xi}')\left(\frac{L_i}{U_i}\right)\left(\frac{\dot{U}_i}{U_i}cos\beta_i - \dot{\beta}_i sin\beta_i\right) + (m_i' + m_{yi}')r_i'\sin\beta_i' = X_{Hi}' + X_{Pi}' + X_{Ri}' \quad (6)$$

$$-(m_i' + m_{yi}')\left(\frac{L_i}{U_i}\right)\left(\frac{\dot{U}_i}{U_i}sin\beta_i - \dot{\beta}_i cos\beta_i\right) + (m_i' + m_{xi}')r_i'\cos\beta_i' = Y_{Hi}' + Y_{Ri}' + Y_{Ii}' + Y_E' \quad (7)$$

$$(I_{zzi}' + i_{zzi}')\left(\frac{L_i}{U_i}\right)^2\left(\frac{\dot{U}_i}{L_i}r_i' + \frac{U_i}{L_i}\dot{r}_i'\right) = N_{Hi}' + N_{Ri}' + N_{Ii}' + N_E' \quad (8)$$

where, m_i' represents non-dimensionalized mass of ship i, m_{xi}' and m_{yi}' represent x, y axis component of non-dimensionalized added mass of ship i. Also, β_i means drift angle of ship i. The subscript H, P, R, I and E mean ship hull, propeller, rudder, interaction effect between two ships and experimental result between ship and sidewall with a mound, respectively. Also, the rudder angle is controlled to keep course as follows:

$$\delta_i = \delta_{0i} - K_1(\psi_i - \psi_{0i}) - K_2 r_i' - K_3(S_{Pi}' - S_{P0i}') \quad \text{..................(9)}$$

where, δ_i, ψ_i, r_i' mean the rudder angle, heading and non-dimensional angular velocity of ship i, respectively. Also, S_{Pi}' is non-dimensionalized distance between ship i using ship length L_i and sidewall with a mound. The subscript "0" indicates initial values, and K_1, K_2, K_3 are control gain constants.

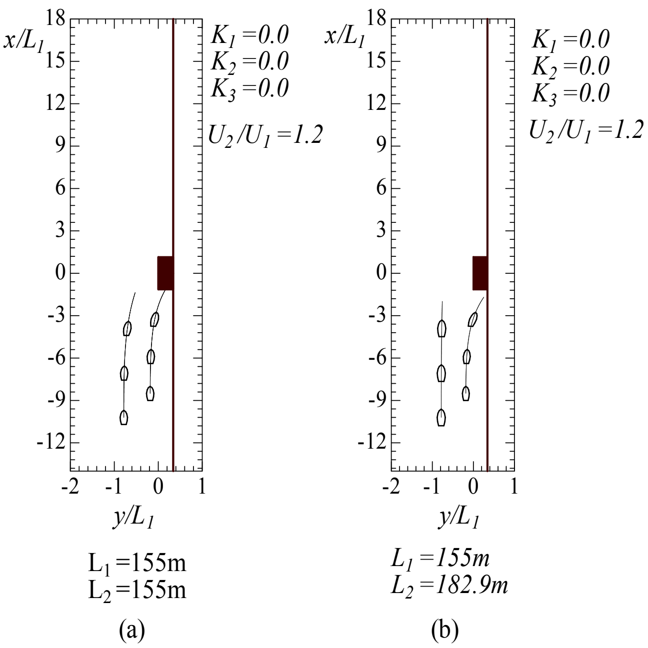

Fig. 2 Variation of ship trajectories without rudder control ($h/d_1 = 1.2$, $S_{P12}/L_1 = 0.6$, $U_2/U_1 = 1.2$)

Fig. 2 shows the result of ship maneuvering simulation with various of L_2/L_1 without rudder control. In this figure, the lateral distance between two ships was taken as 0.6 times of ship length, and the velocity ratio of U_2/U_1 is 1.2 in $h/d_1 = 1.2$. From figure 2, it indicates the following result. In case of 1.18 in L_2/L_1, any yawing moments possibly experienced on approaching the sidewall with a mound due to the interaction effects between two ships and sidewall with a mound show up more strongly in the motion compared to the case of 1.0 in L_2/L_1. Then there was a clear tendency for the vessels to deviate to starboard in response to the interaction effect between two ships and sidewall with a mound. Also, an overtaken and overtaking vessel under the condition of 1.2 in U_2/U_1 are largely deviated from the intended direction, which is mainly attributed to lengthening the mutual effects on their relative position between two vessels. Furthermore, the deviation of overtaken vessel for the case of $L_2/L_1 = 1.0$ is comparatively larger from its intended course, compared to the case of 1.18 in L_2/L_1 even though the lateral distance between two ships is about 0.6 times of ship length.

Fig. 3 represents the effects of ratio of ship length under the conditions that the lateral distance between two ships was taken as 0.6 times of ship length and velocity ratio of U_2/U_1 was taken as 1.2 in $h/d_1 = 1.2$. In this figure, the control gain constants are $K_1, K_2 = 5.0, K_3 = -1.0$, and maximum rudder angle for course keeping is 10 degrees. As shown in figure 3, if the interaction effect was the only factor to be considered, overtaking vessel with maximum rudder angle of 10 degrees can navigate while keeping its original course even though the lateral distance between two ships is about 0.6 times of ship length. However, as shown in case of (a) and (b) in Fig.3, an overtaken vessel is much affected by interaction effect between overtaking vessel and sidewall with a mound.

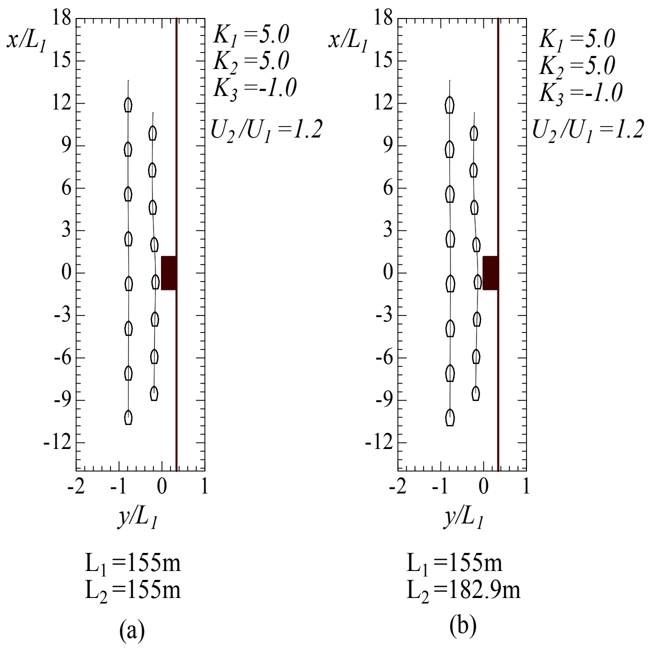

Fig. 3 Variation of ship trajectories with rudder control ($h/d_1 = 1.2$, $S_{P12}/L_1 = 0.6$, $U_2/U_1 = 1.2$)

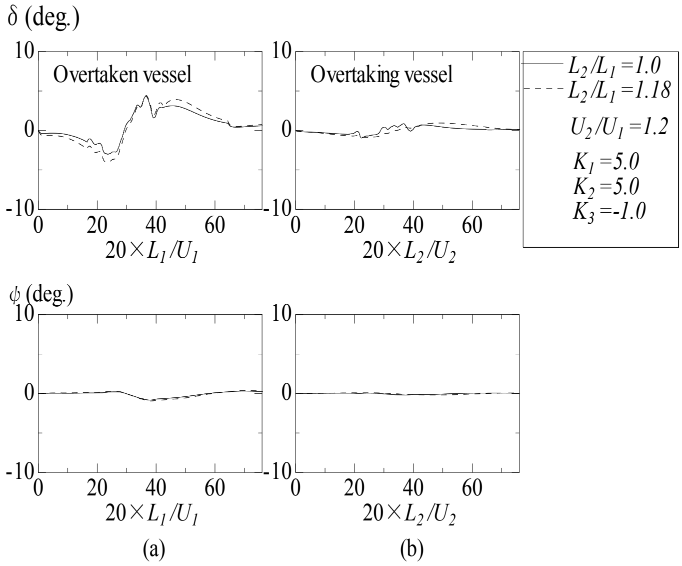

Fig. 4 Time histories of rudder and heading angle for various L_2/L_1 ($\delta_{\max}=10^o$, $S_{P12}/L_1=0.6$)

Fig.4 shows the result of time histories of heading angle and rudder angle for overtaken vessel and overtaking vessel with function of ship length ratio between two ships under the condition of 1.2 in U_2/U_1. Also, the control gain constants for course keeping used in these numerical simulations are $K_1, K_2=5.0, K_3=-1.0$. In this case, the lateral distance between two ships was taken as 0.6 times of ship length in $h/d_1=1.2$. Fig.4 indicates the following result. When and if the lateral distance between two ships is about 0.6 times of ship length, it takes some large for the overtaken vessel to use rudder angle in order to keep its own original course. Also, the variation of heading angle gets some larger in case of overtaken vessel. On the other hand, it is possible to steer the overtaking vessel within the range of 10 degrees in rudder angle and the heading angle displays no changes for the case of overtaking vessel.

The result of safe distance between overtaking vessel and overtaken vessel depending on the velocity ratio and control gain constants under the conditions of $L_2/L_1=1.0$ and $h/d_1=1.2$ is shown in Fig.5. In this figure, the solid line means the velocity ratio, $U_2/U_1=1.2$ and broken line means the velocity ratio, $U_2/U_1=1.5$, respectively. Also, the safe distance signifies the spacing between overtaking vessel and overtaken vessel that two vessels can be operated without causing any collisions in the proximity of sidewall with a mound. In this figure, the x axis shows the rudder angle, and y axis shows the non-dimensional lateral

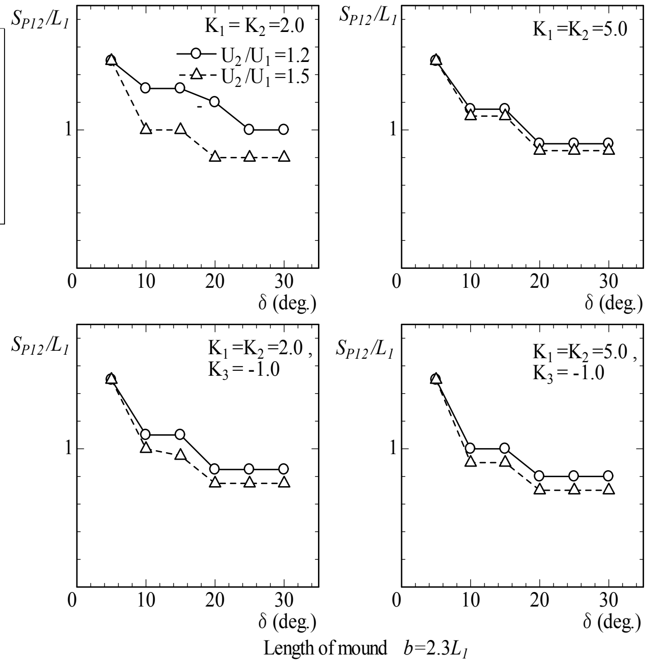

Fig. 5 Minimum safe distance between ships with function of U_2/U_1 and control gain constants ($h/d_1=1.2$, $L_2/L_1=1.0$)

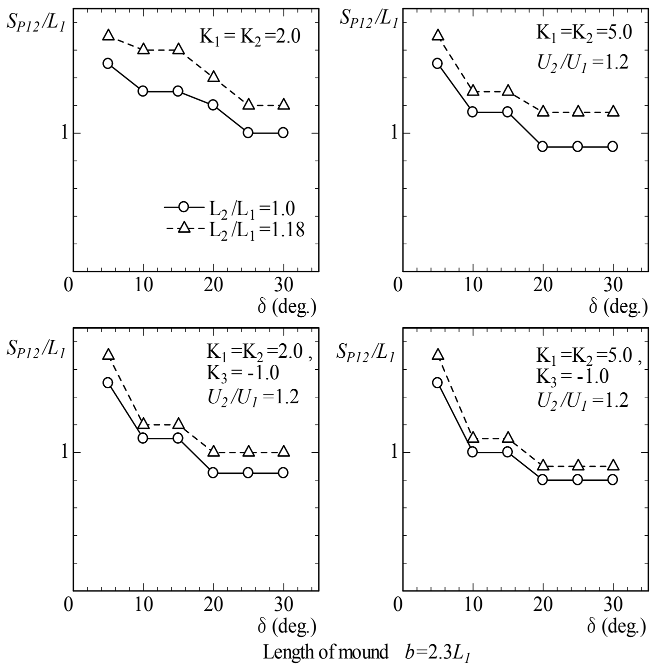

Fig. 6 Minimum safe distance between ships with function of L_2/L_1 and control gain constants ($h/d_1=1.2$, $U_2/U_1=1.2$)

distance between two ships, S_{P12}/L_1. From this figure, it indicates the following result. When and if overtaking vessel passes the overtaken vessel through the proximity of sidewall with a mound, the spacing between two vessels for the safe maneuvering is more needed for the velocity ratio of 1.2, compared to the case of 1.5 regardless of control gain constants. In addition, in case of control gain constants, the spacing between two vessels for the safe maneuvering is required for the control gain constants of $K_1 = K_2 = 2.0$ and $K_1 = K_2 = 5.0$, compared to the cases of $K_1 = K_2 = 2.0, K_3 = -1.0$ and $K_1 = K_2 = 5.0, K_3 = -1.0$.

Also, the result of safe distance between overtaking vessel and overtaken vessel depending on the ship length ratio and control gain constants under the conditions of $U_2/U_1 = 1.2$ and $h/d_1 = 1.2$ is shown in Fig.6. In Fig.6, the solid line shows the ship length ratio, $L_2/L_1 = 1.0$ and broken line shows the ship length ratio, $L_2/L_1 = 1.18$, respectively. From this figure, it indicates the following result. When and if overtaking vessel passes the overtaken vessel through the proximity of sidewall with a mound, the spacing between two vessels for the safe maneuvering is more required for the ship length ratio of 1.18, compared to the case of 1.0 regardless of control gain constants. In the meantime, in case of control gain constants, the spacing between two vessels for the safe maneuvering is some more required for the control gain constants of $K_1 = K_2 = 2.0$ or 5.0, compared to the cases of $K_1 = K_2 = 2.0, K_3 = -1.0$ and $K_1 = K_2 = 5.0, K_3 = -1.0$.

4. Conclusions

A parametric study on the numerical calculations has been conducted on the general cargo ship. From the simulation of ship maneuvering motions on the safe maneuvering between two ships while overtaking in confined waters, the following conclusions can be drawn.

First, in case of the velocity ratio of $U_2/U_1 = 1.2$ under the condition of $L_2/L_1 = 1.0$, both the spacing between two ships and the rudder angle are more needed for the safe maneuvering compared to the case of 1.5 in U_2/U_1 regardless of control gain constants.

Second, in case of control gain constants to keep the original course, the spacing between two vessels for the safe maneuvering is more required for the control gain constant of $K_3 = 0$, compared to the case of $K_3 = -1.0$.

Third, in case of ship length ratio of $L_2/L_1 = 1.0$ under the condition of $U_2/U_1 = 1.2$, the spacing between two vessels for the safe maneuvering is more required compared to the case of 1.18 in L_2/L_1 regardless of control gain constants.

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