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Assessment of Safe Navigation Including the Effect of Ship-Ship Interaction in Restricted Waterways

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제한수역에서 두선박간의 상호간섭력을 포함한 안전항해의 평가

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ABSTRACT : *This paper is mainly concerned with the assessment of safe navigation between ships moving each other in restricted waterways. The manoeuvring simulation was conducted parametrically to propose an appropriate safe speed and distance, which is required to avoid sea accident under the different conditions, such as ship-velocity ratios, ship-length ratios, separation and stagger between ships. The manoeuvring characteristics based on this investigation will be very useful for keeping the safety of navigation from the practical point of ships design and traffic control in confined water.*

KEY WORDS : *Safe navigation, Safe speed and distance, Sea accident, Manoeuvrability*

요　　약 : 이 논문에서는 제한수역에서 항행하는 대형선박들간의 안전항해를 위하여, 해난사고 방지에 필요한 선박들간의 적절한 안전 속력 및 거리를 확보하기 위하여, 두 선박간의 속도비, 선장비, 횡방향 거리 및 종방향 거리를 변수로 하여 조종운동에 관한 시뮬레이션을 행하였다. 이상의 수치 계산 결과는 대형선박들의 왕래가 빈번한 폭주해역에서의 해상교통안전의 측면에서 볼 때 상당히 유용할 것이다.

핵심용어 : 안전항해, 안전 속력 및 거리, 해난사고, 조종성

1. Introduction

From the viewpoint of technical aspects of vessels, they are continuously enlarged in hull size and greatly specialized in structure for the cargo spaces and dramatically automatized in navigating, cargo operating and various other operations, which require high techniques in operating the vessels. However, in spite of the great development of the modern techniques in shipbuilding as these trends of vessels today, many sea accidents of large vessel's in confined waters due to the effect by restricted waterways, such as shallow water effect or inherently restricted nature of waterways have been occurring successively. In particular, proximal navigation of large vessels including overtaking, head-on situation, and congested vessel traffic in these waterways is potentially hazardous. 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 interaction between ships in restricted waterways should be properly understood, and the works on this part have been reported for the past years[1][2][3].

However, in many of the above-mentioned papers, the transient sway force and yaw moment experienced by a ship in transit near other ships was investigated. Thus, the detailed knowledge on manoeuvring characteristic for the safe navigation while avoiding terrible collision between ships is still being required to prevent marine disasters.

In the present paper, the emphasis is on the appropriate safe

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*cklee@vortex.nams.kyushu u.ac.jp +81 90 9727 8235 speed and distance between ships required to avoid sea accident and on the guideline to the design and operation of the ship-waterway system from the viewpoint of marine safety.

2. Theoretical backgrounds

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 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. Both calculation methods and theoretical backgrounds related in this were reported in the previous research work[3], but non-dimensional expression for the lateral force C_{Fi}, and yawing moment C_{Mi}, affecting upon two vessels is given by

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

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

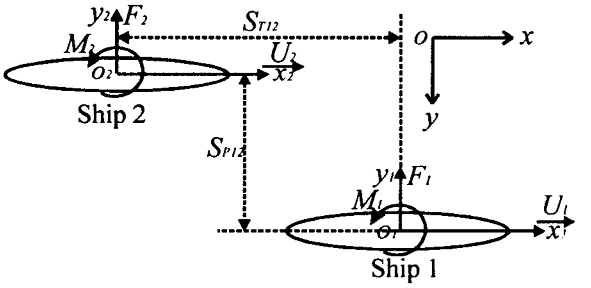


Fig. 1 Coordinate systems

3. Hydrodynamic interaction forces between ships

3.1 Condition of calculation

In this section, the hydrodynamic interaction forces acting on two ships while overtaking and meeting in shallow waters have been examined. A parametric study on the numerical calculations has been conducted on the general cargo ship as shown in Table 1 and Table 2. As shown in Table 2, for the cases of different ratios of 0.5, 1.0 and 1.18 in L_2/L_1 and for the cases of 0.6, 1.2 and 1.5 in U_2/U_1 as the parameters, the hydrodynamic interaction forces between two ships in open sea have been computed. The external forces were not taken into account. 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.

Table 1 Principal particulars of ship

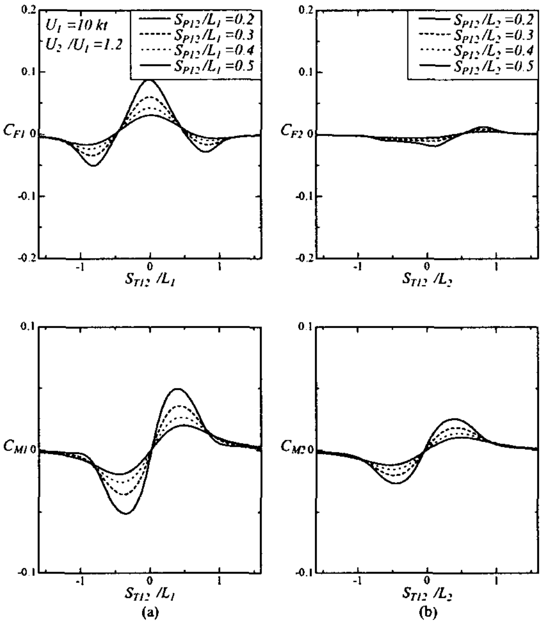
	General cargo ship
Length L(m)	155.0
Breadth B(m)	26.0
Draft d(m)	8.7
Block coef. C_B	0.6978

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

Types	ratio between two 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

3.2 Hydrodynamic interaction forces in case of overtaking situation

Fig.2 shows the result of computed lateral force and yawing moment coefficients for the case of general cargo ship while overtaking. The separation between two ships was chosen to be 0.2 to 0.5 times of a ship length under the conditions of $L_2/L_1 = 1.0$ and $U_2/U_1 = 1.2$. Fig.2 (a) and (b) show the lateral force and yawing moment coefficients for ship 1 and ship 2, respectively. From this figure, it indicates the following result. The overtaken and overtaking vessel experience an attracting force which increases as two vessel approach with each other. When the bow of overtaking vessel approaches the stern of the overtaken vessel, two ships encounter the first hump of the attracting force and a maximum bow-inward 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-outward moment when the longitudinal distance between the midships of two ships is about 0.5 times of a ship length in distance, then the bow-outward moment acting on two vessels due to the sufficient longitudinal distance between two ships are disappeared. For hydrodynamic interaction forces, the effect of ship 1 is quantitatively bigger than the one of ship 2.



(a) (b)

Fig.2 Lateral force and yawing moment coefficients(h/d=1.2)

3.3 Hydrodynamic interaction forces in case of head-on situation

Fig.3 shows the instantaneous force and moment for two general cargo ships approaching each other. The separation between two ships was chosen to be 0.2 to 0.5 times of L_1 under the conditions of 1.0 in L_2/L_1 and U_2/U_1. As expected, the magnitude of values for the force and moment decreases monotonically as separation between ships, S_{P12}/L increases. By moving along the S_T/L axis from left to right, one may visualize these curves as the time history of the interaction force and moment. One observes that during the approach each vessel experiences initially a repulsive force and bow-outward moment. Just as the lateral force becomes attractive, the yawing moment becomes bow-inward. After the midships have crossed, the yawing moment changes to bow-outward again, but the attractive force remains for some time, which may cause the sterns of the vessels to collide.

Fig.4 displays the instantaneous force and moment for two general cargo ships approaching each other under the conditions of 1.0 in L_2/L_1 and U_2/U_1 with function of h/d. As expected, the magnitude of values for the force and moment decreases monotonically as depth-to-draft ratio h/d, increases. From this figure, it indicates the following result. The several reversals of the sign of the yawing moment are of great concern to the helmsman. Another feature observable from these curves is that the vessel for the case of shallow water experiences a larger force and moment than the vessel for the case of deep water.

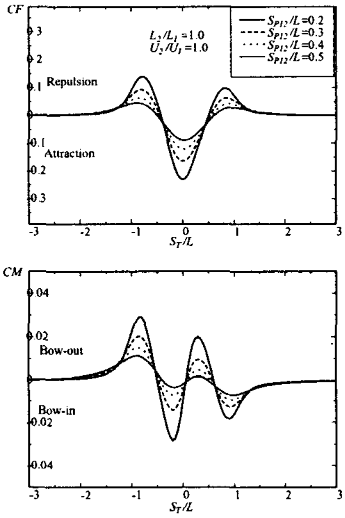


Fig.3 Lateral force and yawing moment coefficients(h/d=1.2)

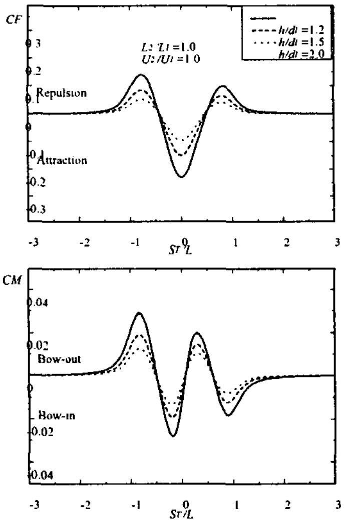


Fig.4 Lateral force and yawing moment coefficients

4. Results and discussion

4.1 Simulation of ship manoeuvring motions

In this section, the ship manoeuvring motions are simulated numerically using the predicted hydrodynamic interaction forces and the ship manoeuvring model of Kijima et al.[4], and the external force and moment acting on two ships in confined water can be expressed as follows:

$$(m_i'+m_{xi}')\left(\frac{L_i}{U_i}\right)\left(\frac{\dot{U}_i}{U_i}\cos\beta_i-\dot{\beta}_i\sin\beta_i\right)+(m_i'+m_{yi}')r_i'\sin\beta_i = X'_{Hi}+X'_{Pi}+X'_{Ri} \quad (2)$$

$$-(m_i'+m_{yi}')\left(\frac{L_i}{U_i}\right)\left(\frac{\dot{U}_i}{U_i}\sin\beta_i+\dot{\beta}_i\cos\beta_i\right)+(m_i'+m_{xi}')r_i'\cos\beta_i = Y'_{Hi}+Y'_{Ri}+Y'_{Ii} \quad (3)$$

$$(I'_{zzi}+i'_{zzi})\left(\frac{L_i}{U_i}\right)^2\left(\frac{\dot{U}_i}{L_i}r_i'+\frac{U_i}{L_i}\dot{r}_i'\right) = N'_{Hi}+N'_{Ri}+N'_{Ii} \quad (4)$$

where m_i' represents non-dimensionalized mass of ship i and m_{xi}',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 subscribt H,P,R,I mean ship hull, propeller, rudder, component of the hydrodynamic interaction forces between two ships. A rudder angle is controlled to keep course as follows:

$$\delta_i=\delta_{0i}-K_1(\psi_i-\psi_{0i})-K_2r_i'-K_3(S'_{Pi}-S'_{P0i}) \quad (5)$$

where δ_i,ψ_i,r_i' represent rudder angle, heading, non-dimensional angular velocity of ship i, and S'_{Pi} is non-dimensionalized predicted course. Subscript '0' indicates initial values.

Fig.5 shows the result of manoeuvring simulation for general cargo ship with various of control gain constants for the case of $U_2/U_1=1.2$. In this case, the separation between two ships, S_{P12} was taken as 0.3 times of a ship length and L_2/L_1 was taken as 1.0 in *h/d*=1.2. The control gain constants used in these numerical simulation are $K_1=K_2=2.0, K_3=0.0$, $K_1=K_2=5.0, K_3=0.0$, $K_1=K_2=2.0, K_3=-1.0$, $K_1=K_2=5.0, K_3=-1.0$, respectively and maximum rudder angle, $\delta_{max}=10''$. As shown in case of (a),(b),(d) in Fig.5, two ships with maximum rudder angle of 10° can navigate safely while keeping its original course even though the separation between ships is 0.3 times of ship length. However, as shown in (c) of Fig.5, an overtaken vessel is somewhat deviated from the original course, which is mainly attributed to lengthening the mutual effects on their relative position between two ships under the condition of $K_1=K_2=2.0, K_3=-1.0$, while it is guided securely with intended direction for the overtaking vessel. However, even though the separation between ships is 0.3 times of ship length, two ships course is not almost deviated from the original direction under the condition of $\delta_{max}=10^\circ$ regardless of the control gain constants because the effect of interaction forces only as parameter is not large.

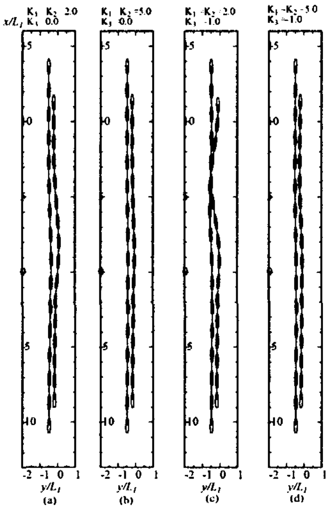


Fig.5 Ship trajectorics with function of control gain constants

The result of time histories with function of the control gain constants is shown in Fig.6. In this case, the separation between two ships was taken as 0.3 times of a ship length and L_2/L_1 was taken as 1.0 in *h/d*=1.2. The control gain constants used in these numerical simulation are $K_1=K_2=2.0, K_3=0.0$, $K_1=K_2=5.0, K_3=0.0$, $K_1=K_2=2.0, K_3=-1.0$, $K_1=K_2=5.0, K_3=-1.0$, respectively and maximum rudder angle, $\delta_{max}=10^\circ$. In case of $K_1=K_2=2.0, K_3=-1.0$, when and if the separation between two ships is 0.3 times of ship 1 that navigate at low speed, it takes long for the ship 1 to maintain maximum rudder angle of 10° in order to keep its own original course. Also, the variation of heading angle of ship 1 ψ_1, gets larger. On the other hand, it's possible enough to steer the ship 2 within the range of 10° in rudder angle and the heading angle ψ_2, shows almost no changes for the case of ship 2.

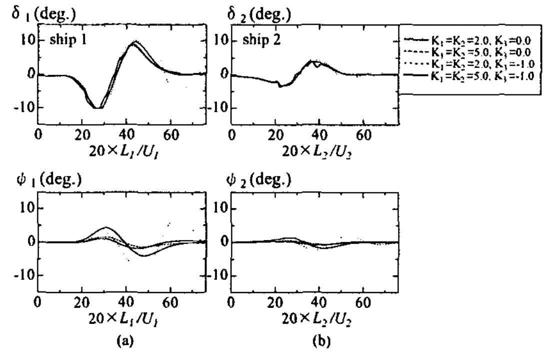


Fig.6 Time histories of rudder and heading angle with function of control gain constants

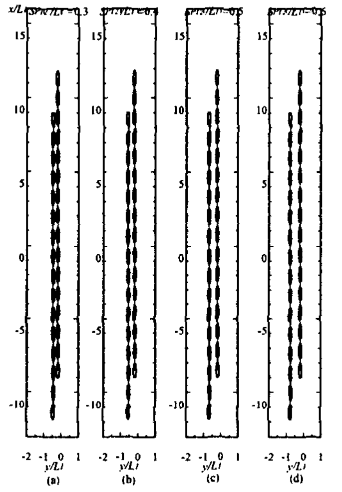


Fig.7 Ship trajectories of head-on situation

Fig.7 shows the result of manoeuvring simulation for head-on situation of general cargo ship with various of separation between two ships, S_{P12} for the case of $U_2/U_1=1.0$. In this case, the separation between two ships, S_{P12} was chosen to be 0.3 to 0.6 times of a ship length under the condition of $L_2/L_1=1.0$. The control gain constants used in these numerical simulation are $K_1=K_2=5.0, K_3=-1.0$, and maximum rudder angle $\delta_{max}=5°$. In this case, two vessel's course is not almost deviated from the original direction under the condition of $\delta_{max}=5°$ even though S_{P12} is about 0.3 times of ship length.

4.2 Assessment of Safe Navigation Based on the Simulation of Ship Manoeuvring Motions

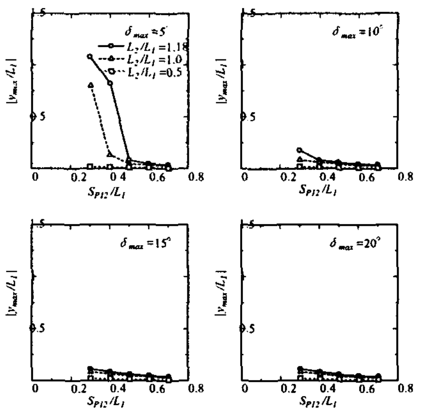


Fig.8 Deviated maximum lateral distance from the original course

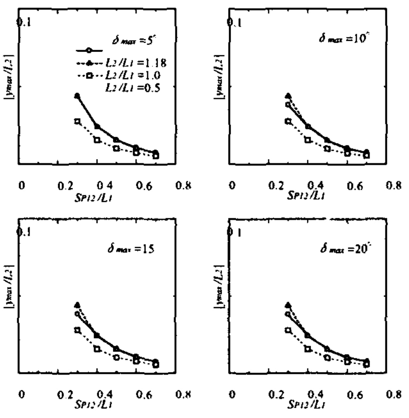


Fig.9 Deviated maximum lateral distance from the original course

Fig.8 and Fig.9 show the results for deviated maximum lateral distance from the original course with function of the L_2/L_1 for the case of overtaken and overtaking vessel. The lateral separation between two ships was chosen to be 0.3 to 0.7 times of L_1 under the condition of $U_2/U_1=1.2$. The control gain constants used in these numerical simulation are $K_1=K_2=5.0, K_3=-1.0$ in h/d=1.2. From Fig.8, nondimensionalized lateral distance between two ships is required for the ship-length ratio of 1.18, compared to the cases of 1.0 and 0.5 regardless of the maximum rudder angle. Also, regardless of the L_2/L_1, the results represent almost same tendency. However, the magnitude of results for the maximum lateral distance deviated from the original course is almost disappeared if lateral separation between two ships is about

$0.5L_1$ under the condition of $\delta_{max} = 5°$ regardless of L_2/L_1. On the other hand, from Fig.9, an overtaking vessel's course is not almost deviated from the original course under the condition of $\delta_{max} = 5°$ regardless of ship-length ratio, even though lateral separation between two ships is about $0.3L_1$.

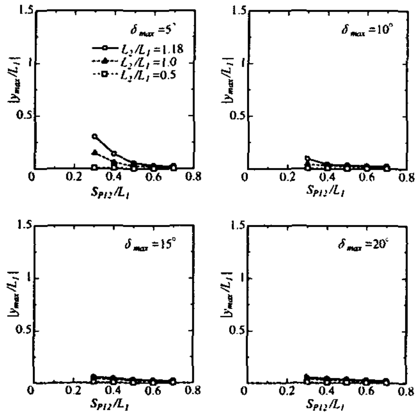


Fig.10 Deviated maximum lateral distance from the original course

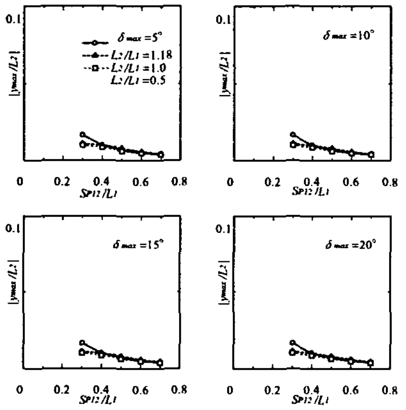


Fig.11 Deviated maximum lateral distance from the original course

The deviated maximum lateral distance from the original course with various of L_2/L_1 for the case of $U_2/U_1 = 1.5$ are shown in Fig.10 and Fig.11. As expected, from Fig.10, nondimensionalized lateral distance between two ships is required for the ship-length ratio of 1.18, compared to the cases of 1.0 and 0.5. However, in case of $\delta_{max} = 10°$, the magnitude of results for the maximum lateral distance deviated from the original course is almost disappeared, even though lateral separation between two ships is about $0.3L_1$. Furthermore, an overtaken vessel with ranges of 5 degrees in maximum rudder angle is not almost deviated from the original course regardless of L_2/L_1, if the lateral separation between two ships is $0.5L_1$. In the meantime, from Fig.11, an overtaking vessel's course is not almost deviated from the original course under the condition of $\delta_{max} = 5°$ regardless of ship-length ratio, even though lateral separation between two ships is about $0.3L_1$.

5. Conclusions

The following conclusions can be drawn from the simulation of ship manoeuvring motions on the safe navigation between ships while overtaking and head-on situation in shallow waters.

Firstly, lateral distance between ships and rudder angle are much more needed for the case of overtaking situation than for the case of head-on situation. Secondly, regardless of the control gain constants and ship-length ratio, the consideration of lateral distance between ships and rudder angle are much more required for the ship-velocity ratio of $U_2/U_1 = 1.2$ than for the cases of 1.5 and 0.6, respectively. Also, regardless of the ship-velocity ratio, an overtaking and overtaken vessel can be maneuvered safely without deviating from the original paths under the following conditions; the distance between two vessels is approximately kept at 0.5 times of ship 1 and 5 through 10 degrees of range in maximum rudder angle. The manoeuvring characteristics based on this investigation will be very useful for keeping the safety of navigation from the practical point of ships design and traffic control in confined water.

References

[1] Yeung, R.W.(1978):On the Interactions of Slender Ships in Shallow Water, Journal of Fluid Mechanics, Vol.85.

[2] Davis, A.M.J.(1986):Hydrodynamic Effects of Fixed Obstacles on Ships in Shallow Water, Journal of Ship Research, Vol.30.

[3] Kijima, K., Furukawa, Y. and Qing, H.(1991):The Interaction Effects between Two Ships in the Proximity of Bank Wall, Trans. of the West-Japan Society of Naval Architects, Vol.81.

[4] Kijima, K., Nakiri, Y., Tsutsui, Y. and Matsunaga, M.(1990):Prediction Method of Ship Manoeuvrability in Deep and Shallow Waters, Proceedings of MARSIM and ICSM 90.