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Investigation of ship maneuvering with hydrodynamic effects between ship and bank

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Abstract

When a vessel navigates in confined waters, such as in a harbour or narrow channel, it is well known among experienced pilots that the ship handling is greatly affected by the hydrodynamic forces and moments acting between ship and bank or sidewall of the channel. The hydrodynamic forces between ship and bank can be assumed to be functions of the water depth, longitudinal and lateral distance along with ship's velocity. In this research, the characteristic features of the hydrodynamic forces variation during the encounter are described and illustrated, and furthermore the effect of water depth and the spacing between ship and bank with an angle are summarized and discussed. When a vessel is approaching the tip of a wedge-shaped bank, it may encounter a dangerous tendency of collision due to the combined effect of the attracting sway force and a bow-in moment. For water depth to draft ratio (h/d) less than about 2.5, the hydrodynamic force and yaw moment between ship and bank increase sharply as h/d decreases. Also, the hydrodynamic effects decrease as separation between ship and bank (S_P)increases and approach to zero when the vessel moves to the wedge-shaped bank under the condition of $S_P = 0.5L$.

Keywords: Ship maneuvering; Hydrodynamic force; Bank effect; Separation between ship and bank; Water depth

1. Introduction

The most typical situation of hydrodynamic force between ship and bank or sidewall is encountered in confined waters. Besides, the magnitudes of interaction effects are several times larger in confined water when compared to infinite water. The hydrodynamic force between ships and between ship and bank or sidewall in the proximity of bank affects the ship maneuvering and course keeping of the ships. When a ship travels in restricted waterways such as in a harbour or narrow channel, it is widely accepted that hydrodynamic forces acting between ship and bank are the main parameters in ship maneuvering. For this to be possible, the hydrodynamic forces between vessel and bank or sidewall of the channel in confined waters should be properly understood, and the work on this part has been reported for the past years. [1, 2] reported the force and moment on a slender body of revolution moving near a wall and some theory for ship maneuvering. Similar work was reported by [3-9] studied the interaction effects between two ships in the proximity of a bank wall. [10] investigated the bank effect of ship maneuverability in a channel with varying width. Also, [11] analyzed ship maneuvering motions in the proximity of bank. Despite past investigations, a detailed knowledge of the maneuvering characteristic for safe navigation between ship and bank or sidewall of the channel is still being required to prevent further marine disasters.

2. Formulation of the problem

Consider a slender vessel of length L moving parallel to one side of a wedge-shaped obstacle of angle

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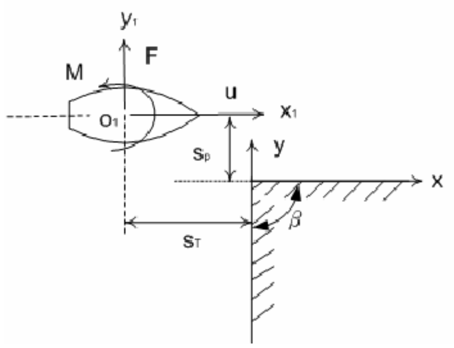

Fig. 1. Coordinate system.

β at a constant velocity U in an inviscid fluid of uniform depth h. The coordinate system fixed on ship is shown by $o_1 - x_1 y_1$ in Fig. 1. In Fig. 1, S_P and S_T are lateral and longitudinal distance between ship and angled bank. 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 model of the ship can be considered. The velocity potential $\phi(x,y,z;t)$, which expresses the disturbance generated by the motion of the ship, should satisfy the following conditions:

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

$$\left.\frac{\partial\phi}{\partial n}\right|_c=0 \quad (2)$$

$$\left.\frac{\partial\phi}{\partial z}\right|_{z=\pm h}=0 \quad (3)$$

$$\left.\frac{\partial\phi}{\partial n}\right|_B=U(t)(n_x) \quad (4)$$

$$\phi\rightarrow 0 \quad at \quad \sqrt{x_1{}^2+y_1{}^2+z_1{}^2}\rightarrow\infty \quad (5)$$

where, B is the body surface of ship (n_x) is the x_1 component of the unit normal $\vec{n}$ interior to B. The following assumptions of slenderness parameter ε are made to simplify the problem.

$$L=o(1),\ B=o(\varepsilon),\ d=o(\varepsilon),\ h=o(\varepsilon),\ S_P=o\ (1)$$

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 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 can be expressed as follows [9]:

$$\begin{aligned}\Phi(y_1,z_1;x_1;t)&=U(t)\Phi^{(1)}(y_1,z_1)\\&+V^*(x_1,t)\Phi^{(2)}(y_1,z_1)+f(x_1,t)\end{aligned} \quad (6)$$

where, $\Phi^{(1)}$ and $\Phi^{(2)}$ are unit velocity potentials for longitudinal and lateral motion, V^* represents the cross-flow velocity at $\sum(x_1)$, and f 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 in the outer region is represented by distributing sources and vortices along the body axis [9]:

$$\begin{aligned}&\phi(x,y,t)=\\&\frac{1}{2\pi}\{\int_L\sigma(s,t)(\log\sqrt{(x-\xi)^2+(y-\eta)^2}+H^{(\sigma)}(x,y;\xi,\eta))ds\\&+\int_{Lw}\gamma(s,t)(\tan^{-1}\left(\frac{y-\eta}{x-\xi}\right)+H^{(\gamma)}(x,y;\xi,\eta))ds\}\end{aligned} \quad (7)$$

where, $\sigma(s,t)$ and $\gamma(s,t)$ are the source and vortex strengths, respectively. L and w denote the flow field along the ship and vortex wake shed behind the ship, respectively. ξ and η represent the source and vortex point. $H^{(\sigma)}$ and $H^{(\gamma)}$ are any functions on the wedge-shaped bank wall.

2.2 Asymptotical match of inner and outer problems

The unknown source strength σ and vortex strength γ cannot be determined from the outer problem alone. The method of matched asymptotic is applied to both the inner and outer problems to obtain the necessary relations. By matching terms of Φ and ϕ that have similar nature, the following integral equation for γ can be obtained as follows [12]:

$$\begin{aligned}&\frac{1}{C(x_1)}\int_{x_1}^{\frac{L}{2}}\gamma(\xi,t)d\xi-\frac{1}{\pi}\int_{-\infty}^{\frac{L}{2}}\gamma(\xi,t)\left[\frac{1}{x_1-\xi}+\frac{\partial H^{(\gamma)}}{\partial y_1}\right]d\xi\\&=-\frac{U}{2\pi H}\int_{-\frac{L}{2}}^{\frac{L}{2}}S'(\xi)\frac{\partial H^{(\sigma)}}{\partial y_1}d\xi\end{aligned} \quad (8)$$

The hydrodynamic forces acting on ship can be obtained by solving this integral equation for γ. The solution γ of Eq. (8) should satisfy the additional conditions:

$$\begin{aligned} &\gamma(x_1,t)=\gamma(x_1) \quad for \quad x_1 \prec -\frac{L}{2}, \\ &\int_{-\infty}^{\frac{L}{2}} \gamma(\xi,t)d\xi = 0, \quad \gamma(x_1 = -\frac{L}{2},t) = -\frac{1}{U}\frac{d\Gamma}{dt} \end{aligned} \tag{9}$$

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

$$\begin{aligned} &F(t) = -h\int_{-\frac{L}{2}}^{\frac{L}{2}} \Delta P(x,t)dx_1 \\ &M(t) = -h\int_{-\frac{L}{2}}^{\frac{L}{2}} x_1 \Delta P(x_1,t)dx_1 \end{aligned} \tag{10}$$

where Δp is the difference of linearized pressure about the x_1 -axis and non-dimensional expression for the lateral force, C_F , and yawing moment, C_M , affecting two vessels is given by

$$C_F = \frac{F}{\frac{1}{2}\rho L d U^2}, \quad C_M = \frac{M}{\frac{1}{2}\rho L^2 d U^2} \tag{11}$$

where, L is the ship length of ship and d is the draft of ship. ρ is the water density.

3. Prediction of hydrodynamic forces between ship and wedge-shaped bank of angle

In this section, the hydrodynamic forces acting on a vessel while approaching and moving parallel to one side of a wedge-shaped bank of angle β in a harbour have been examined. A parametric study on the numerical calculations has been conducted on chemical tanker ship as shown in Table 1. The condition of typical approaching and moving parallel to one side of a wedge-shaped bank of angle was investigated as shown in Fig. 1. If the speed of ship (denoted as U) is maintained at 3 kt, the separation between ship and wedge-shaped bank varies, such as 0.1, 0.2, 0.3, 0.4, 0.5 times of the ship length. Also, the water depth was chosen to be 1.2 to 4.0 times of a ship draft under the condition of 3 kt in ship velocity, respectively.

Table 1. Principal particulars.

G/T	3,800 ton
Length L_{PP}	98.60m
Breadth B	16.50m
Draft d	6.94m
Block Coefficient C_B	0.763

Figs. 2 and 3 display the computed hydrodynamic forces and moments between vessel and wedge-shaped bank of angle ($\beta = 90^o$). In these figures, the separation between ship and bank was chosen to be 0.1 to 0.5 times of the ship length under the condition of 2.0 in h/d. The solid lines show the result of hydro dynamic forces for the case of 0.1 times of a ship length. The dashed lines mean the result for the case of 0.2 times of a ship length, and the dotted lines show the result for the case of 0.3 times of a ship length. The dash dot lines mean the result for the case of 0.4 times of a ship length. From these figures, the vessel experiences an attracting force that increases as the vessel approaches the wedge-shaped bank of angle ($\beta = 90^o$). When the bow of the vessel approaches the tip of the angled bank, the vessel encounters the first hump of the attracting force and a small bow-in moment. The maximum repulsive force

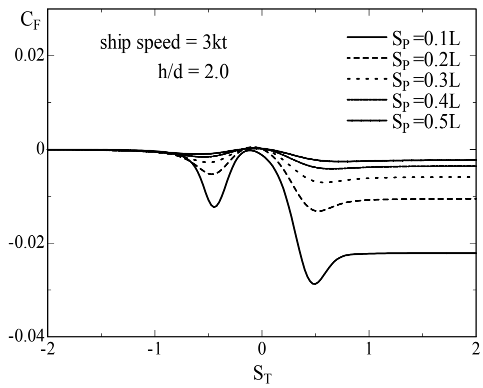

Fig. 2. Computed hydrodynamic forces acting on a ship passing by a wedge-shaped bank.

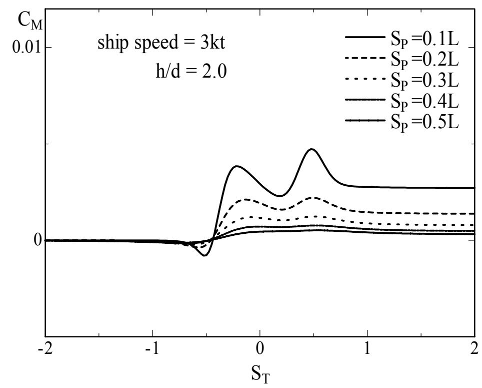

Fig. 3. Computed hydrodynamic moments acting on a ship passing by a wedge-shaped bank.

value is achieved when the midship of the vessel passes the tip of the wedge-shaped bank. Then the sway force reverses to attain the steady attracting force associated with the motion alongside an infinite bank. The vessel experiences a maximum bow-out moment when the stern of the vessel is about at the tip of the wedge-shaped bank, then there is a steady bow-out moment acting on the vessel as it leaves the tip of the wedge-shaped bank.

Figs. 4 and 5 display the computed hydrodynamic forces and moments between vessel and wedge-shaped bank of angle ($\beta = 90^o$) for different water depth. In these figures, the effect of hydrodynamic forces and moments acting on the vessel passing by a wedge-shaped bank become bigger as the water depth decreases, compared to the case of deep sea. For $S_P = 0.1L$ under the condition of shallow water, the wedge-shaped bank generates the largest disturbance.

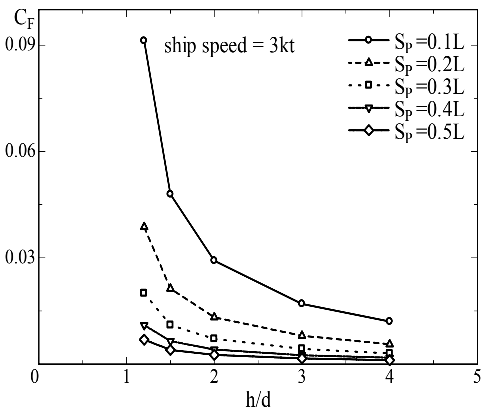

Fig. 4. Computed hydrodynamic forces acting on a ship passing by a wedge-shaped bank for different water depth.

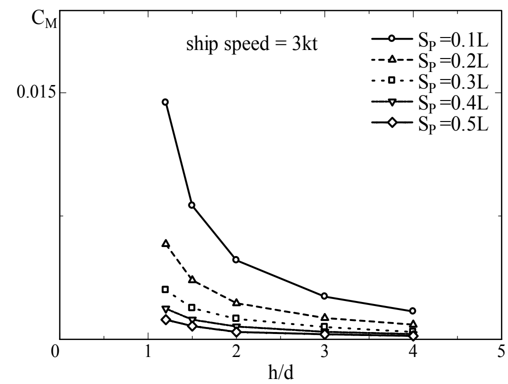

Fig. 5. Computed hydrodynamic moments acting on a ship passing by a wedge-shaped bank for different water depth.

It is found that there is a dangerous tendency to force the stern of the vessel moving towards the bank after the vessel has just passed the tip of the wedge-shaped bank.

3.1 Simulation of ship maneuvering motion under the influence of interaction effect

In the meantime, the mathematical model of ship maneuvering motion under the influence of interaction effect can be expressed as follows (Kijima, 1990):

$$\begin{aligned}&(m' + m_x')\left(\frac{L}{U}\right)\left(\frac{\dot{U}}{U}\cos\beta - \dot{\beta}\sin\beta\right)\\&+(m' + m_y')r'\sin\beta' - (m_x' - m_y')\frac{V_c}{U}r'\sin(\psi' - \alpha)\\&= X_H' + X_P' + X_R' + X_W'\end{aligned} \tag{12}$$

$$\begin{aligned}&-(m' + m_y')\left(\frac{L}{U}\right)\left(\frac{\dot{U}}{U}\sin\beta - \dot{\beta}\cos\beta\right)\\&+(m' + m_x')r'\cos\beta' - (m_y' - m_x')\frac{V_c}{U}r'\cos(\psi' - \alpha)\\&= Y_H' + Y_R' + Y_I' + Y_W'\end{aligned} \tag{13}$$

$$\begin{aligned}&(I_{zz}' + i_{zz}')\left(\frac{L}{U}\right)^2\left(\frac{\dot{U}}{L}r' + \frac{U}{L}\dot{r}'\right)\\&= N_H' + N_R' + N_I' + N_W'\end{aligned} \tag{14}$$

where, m' represents non-dimensionalized mass of ship, m_x' and m_y' represent x, y axis components of non-dimensionalized added mass of ship, β means drift angle of ship, respectively. The subscripts H, P, R, I and W mean ship hull, propeller, rudder, component of the hydrodynamic force between ship and bank and wind, and also, V_c, α, ψ mean current velocity, current direction and heading angle of ship. X, Y and N represent the external force of x, y axis and yaw moment about the center of gravity of the ship. A rudder angle is controlled to keep course as follows:

$$\delta = \delta_0 - K_1(\psi - \psi_0) - K_2 r' \tag{15}$$

where δ, r' represent rudder angle, non-dimensional angular velocity of ship. 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 influence of interaction effect are simulated numerically using the predicted hydrodynamic forces acting on the vessel while approaching and moving parallel to one side of a wedge-shaped bank of angle β in restricted waterways.

Fig. 6. Result of simulation under the influence of bank effect ($S_P = 0.1L,\ \ \delta = 0^o$).

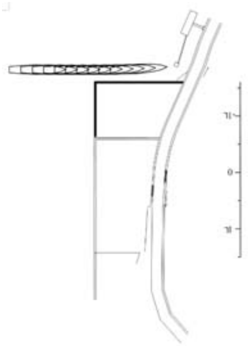

Fig. 7. Result of simulation under the influence of bank effect ($S_P = 0.2L,\ \ \delta = 0^o$).

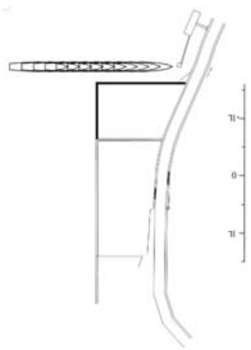

Fig. 8. Result of simulation under the influence of bank effect ($S_P = 0.3L,\ \ \delta = 0^o$).

Figs. 6, 7 and 8 show the result of ship maneuvering simulation with function of the separation between ship and wedge-shaped bank under the conditions, that water depth to draft ratio (h/d) and rudder angle were taken as 2.0 and 0^o, respectively. In these figures, the wind and current effect was not taken into account, and it is a simulation result regarding only interaction between ship and bank. As shown in Fig. 6 and Fig. 7, when the vessel is approaching the tip of the bank, the vessel deviates from the original course due to the combined effect of the attracting sway force and a bow-in moment. However, as shown in Fig. 8, the vessel's course is not almost deviated from the original direction because the interaction effect between ship and bank is not large under the condition of $S_P = 0.3L$.

Figs. 9 and 10 show the result of ship maneuvering simulation with function of the separation between

Fig. 9. Result of simulation under the influence of bank effect ($S_P = 0.1L,\ \ \delta = 10^o$).

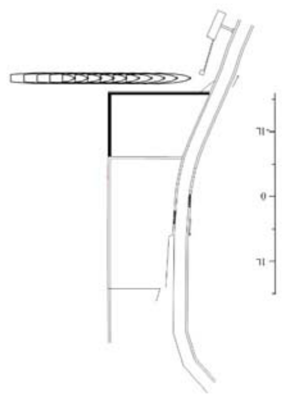

Fig. 10. Result of simulation under the influence of bank effect ($S_P = 0.2L,\ \ \delta = 10^o$).

ship and wedge-shaped bank under the conditions that water depth to draft ratio (h/d) and rudder angle were taken as 2.0 and 10^o, respectively. In these figures, the wind and current effect was not taken into account. As shown in Figs. 9 and 10, in case of $S_P = 0.1L$, there was a tendency for the vessel to deviate to port, compared to the case of $S_P = 0.2L$. It indicates that the rudder force of vessel moving at a low speed is not sufficient to control hydrodynamic forces and moments between ship and wedge-shaped bank under the condition of $S_P = 0.1L$.

5. Conclusion

With the assumption that the free surface is 'rigid', the hydrodynamic forces and moments acting on a vessel while approaching and moving parallel to one side of a wedge-shaped bank of angle β in restricted waterways have been examined. From the above numerical analysis one can conclude that:

When a vessel is approaching the tip of a wedge-shaped bank of angle, it may encounter a potentially hazardous situation during its approach. This arises from the combination of a sway force attracting it toward the wedge-shaped bank and a bow-in moment that changes its heading.

For the effect of water depth, it can be seen that the hydrodynamic force and moment decrease slowly and approach a constant value as h/d increases. Also, for h/d less than about 2.5, the hydrodynamic force and yaw moment increase sharply as h/d decreases.

In the case of the effect of ship to bank separation, it shows that the hydrodynamic force and moment decrease as S_P increases and approach to zero when the vessel moves the wedge-shaped bank under the condition of $S_P = 0.5L$.

This research has further extended the study of hydrodynamic forces between ships in the proximity of bank in restricted waterways, such as in a harbour or narrow channel for a few more practical and complicated situations.

With the same theory and method, the present research will be useful for prediction of ship maneuverability at the initial stage of design, for automatic control systems of ships in confined and/or congested waters, for discussion of marine traffic control system and for construction of harbor.

Acknowledgments

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Nomenclature

ε	:	Slenderness parameter
C_F , C_M	:	Dimensionless hydrodynamic force and yaw moment of ship
K_1 , K_2	:	Control gain constant
L , B , d	:	Ship length, breadth, draught of ship
m'	:	Non-dimensionalized mass of ship
m_x'	:	x axis components of Non-dimensionalized added mass of ship
m_y'	:	y axis components of Non-dimensionalized added mass of ship
σ , γ	:	Source and vortex strength
S_P , S_T	:	Lateral and longitudinal distance between ship and wedge-shaped bank
ξ , η	:	Source and vortex point
Δp	:	Difference of linearized pressure about x_1-axis
U	:	Ship velocity of ship
V_W, ν, ψ , β	:	Wind velocity, wind direction, heading angle, drift angle of ship
X, Y and N	:	External force of x, y axis and yaw moment about center of gravity of ship
δ, r'	:	Rudder angle and non-dimensional angular velocity of ship

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