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# Numerical study of hydrodynamic interaction on a vessel in restricted waterways

Chun-Ki Lee

*Underwater Vehicle Research Center, Korea Maritime University, Pusan, Korea*

**ABSTRACT:** *The hydrodynamic interaction between ship and bank can't be neglected when a vessel is app- roached toward the tip of a wedge-shaped bank in restricted waterways, such as in a harbor, near some fixed obstacles, or in a narrow channel. In this paper, the characteristic features of the hydrodynamic interaction acting on a slowly moving vessel in the proximity of a wedge-shaped bank are described and illustrated, and the effects of water depth and the spacing between ship and wedge-shaped bank are summarized and discussed based on the slender body theory. From the theoretical results, it indicated that the hydrodynamic interactions decrease as wedge-shaped bank of angle $\beta$ in-creases. For water depth to draft ratio less than about 2.0, the hydrodynamic interactions between ship and bank in-crease sharply as h/d decreases, regardless of the wedge-shaped bank of angle $\beta$. Also, for lateral separation more than about 0.2L between ship and wedge-shaped bank, it can be concluded that the bank effects decrease largely as the separation increases.*

***KEY WORDS:*** Hydrodynamic interaction; Bank effect; Water depth effect; Spacing between ship and bank; Slender body theory; Restricted waterways.

## NOMENCLATURE

B : Wedge-shaped bank of angle
$C_F$, $C_M$ : Dimensionless hydrodynamic force and yaw moment of ship
$\Phi$ : Velocity potential
$H^{(\sigma)}$, $H^{(\gamma)}$ : Functions on the wedge-shaped bank wall
$\Delta$P : Difference of linearized pressure about $x_1$-axis
$\xi$, $\eta$ : Source and vortex point
$U$ : Ship velocity
B : Breadth of ship
d : Draught of ship
$\varepsilon$ : Slenderness parameter
h : Water depth
$L$ : Ship length
$\sigma$, $\gamma$ : Source and vortex strength
$S_P$, $S_T$ : Lateral and longitudinal distance between ship and wedge-shaped bank

## INTRODUCTION

Recently enormous bridges are being built near island and channel, and these sea areas are generally main waterways for vessels, resulting in traffic congestion of numerous vessels. When side walls or bridge exist in this kind of sea areas, moving vessels will have some significant restrictions on sailing area. Generally when large vessel sails through narrow waterway com-pared to driven ship breadth or too shallow waterway compared to ship draught, influence from interaction force of side walls can be considered, and this kind of interaction force also can affect the vessel which is controlling its motion. In this kind of limited waterways the captain or pilot of vessel will experience more difficulties compared to ocean sailing. Especially when numerous amount of vessel continues to pass and therefore causing traffic congestion, and complex combination

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Corresponding author: *Chun-Ki Lee*
e-mail: *leeck@hhu.ac.kr*

of hydrody-namic force from large vessel sailing near side walls, shallow water effect, and other external forces disrupts while controlling the vessel, possibility of leading to ocean accidents without careful intention of captain or pilots. Therefore verification of interrelated force between vessel and side wall needs to be clarified in order to prevent such kind of accidents. On the other side, the work of interaction force between vessels and waterways or side walls have been made recently by researchers. Newman (1965, 1969) investigated the hydrodynamic force on a slender body of revolution moving near a wall. Similar work was reported by (Davis, 1986; Norrbin, 1974; Yeung and Tan, 1980). Also, Kijima et al. (1991) and Yasukawa (1991, 2002) stu-died the hydrodynamic interaction effects between ship and some obstacles. Despite the past investigations, the influence de-pending on the shape of side-walls still needs to be considered. Changes in interaction force depending on the shape of side walls needs to be clearly estimated, also in the perspective of safe navigation, this paper will consider the correlation between side walls and large vessels for the sake of reducing sea accidents in narrow waterways, and create a base for narrow sail safety system in narrow waterways. Therefore in this paper when large vessel navigates near the wedge-shaped side walls, variables such as side walls shape, depth of water, and vertical and horizontal distance between side walls and vessel can be considered in order to clearly estimate the interaction forces between them.

## FORMULATION

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

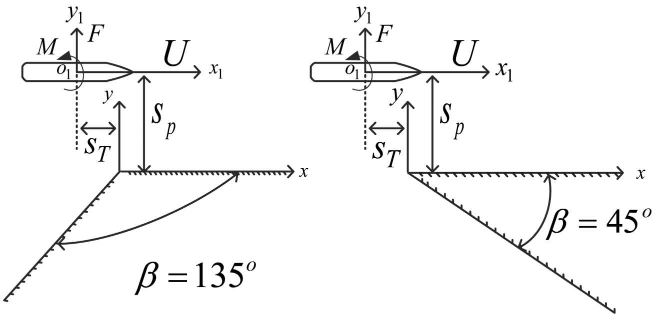

Fig. 1 Coordinate system.

The velocity potential $\phi(x, y, z; t)$ which expresses the disturbance generated by the motion of the ship, should satisfy the following conditions:

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

$$\left.\frac{\partial \phi}{\partial n}\right|_C = 0 \tag{2}$$

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

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

$$\phi \to 0 \text{ at } \sqrt{x_1^2 + y_1^2 + z_1^2} \to \infty \tag{5}$$

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.

$$L = 0(1),\ B = 0(\varepsilon),\ d = 0(\varepsilon),\ h = 0(\varepsilon),\ S_P = 0(1)$$

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

## INNER AND OUTER SOLUTION

The velocity potential Φ in the inner region can be replaced by the velocity potential representing two-dimensional problem 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 (Kijima et al., 1991):

$$\Phi(y_1,z_1;\,x_1;t) = U(t)\Phi^{(1)}(y_1,z_1) + V^{*}(x_1,t)\Phi^{2}(y_1,z_1) + f(x_1,t) \tag{6}$$

where, $\Phi^{(1)}$ and $\Phi^{(2)}$ are unit velocity potentials for longitudinal and lateral motion, $V^{*}$ represents the cross flow velocity at $\Sigma(x_1)$ and $f$ is a term being constant in each cross-section plane, which is necessary to match the inner to the outer solution. Finally, the outer limit of the velocity potential Φ is written as follows (Kijima et al., 1991):

$$\lim_{|y_1|>>\varepsilon}\Phi(y_1,z_1;\,x_1;t) = -\frac{U(t)S'(x_1)}{4h}|y_1| + V^{*}(x_1,t)\{y_1 \pm C(x_1)\} + f(x_1,t) \tag{7}$$

where, $S(x_1)$ is area of the cross section of ship at $x_1$, and $S'(x_1) = dS(x_1)/dx_1$, and the blockage coefficient $C(x_1)$ is estimated by Taylor (1973)'s formula. In the meantime, the velocity potential $\phi$ in the outer region is represented by distri-buting sources and vortices along the body axis (Kijima et al., 1991):

$$\phi(x,t;t) = \frac{1}{2\pi}\left\{\begin{array}{l}\int_{L_j}\sigma(s,t)G^{(\sigma)}(x,y;\xi,\eta)ds \\ +\int_{L_j w_j}\gamma(s,t)G^{(\gamma)}(x,y;\xi,\eta)ds\end{array}\right\} \tag{8}$$

where, $\sigma(s,\,t)$ and $\gamma(s,\,t)$ are the source and vortex strengths, respectively. $L_j$ and $w_j$ denote the integration along ship and vortex wake shed behind the ship, respectively. $\xi$ and $\eta$ represent the source and vortex point. The Green function $G^{(\sigma)}(x,y;\xi,\eta)$ and $G^{(\gamma)}(x,y;\xi,\eta)$ are defined as follows:

$$G^{(\sigma)}(x,y;\xi,\eta) = \ln\sqrt{(x-\xi)^2+(y-\eta)^2} + H^{(\sigma)}(x,y;\xi,\eta) \tag{9}$$

$$G^{(\gamma)}(x,y;\xi,\eta) = \tan^{-1}\left(\frac{y-\eta}{x-\xi}\right) + H^{(\gamma)}(x,y;\xi,\eta) \tag{10}$$

$H^{(\sigma)}$ and $H^{(\gamma)}$ are harmonic functions arising from existence of the wedge-shaped bank wall. They are determined to satisfy the below conditions.

$$\left[\frac{\partial G^{(\sigma)}}{\partial n}\right]_C = 0,\ \left[\frac{\partial G^{(\gamma)}}{\partial n}\right]_C = 0 \tag{11}$$

By expanding $\phi$ for $y_1$ and translating the coordinate system, the inner limit of $\phi$ is obtained:

$$\begin{aligned}\lim_{|y_1|<<1}\phi(x,y;t) = {} & \frac{1}{2\pi}\int_{L_j}\sigma(s,t)G^{(\sigma)}(x_1,0;\xi,0)ds + \frac{1}{2\pi}\int_{L_j w_j}\gamma(s,t)G^{(\gamma)}(x_1,0;\xi,0)ds \\ & \pm\frac{1}{2}\int_{x_1}^{\frac{L}{2}}\gamma(\xi,t)d\xi + \frac{\sigma(x_1)}{2}|y_1| + \left[\frac{1}{2\pi}\int_{L_j}\sigma(s,t)\frac{\partial H^{(\sigma)}}{\partial y_1}(x_1,0;\xi,0)ds\right. \\ & \left. + \frac{1}{2\pi}\int_{L_j w_j}\gamma(s,t)\left\{\frac{1}{x_1-\xi} + \frac{\partial H^{(\gamma)}}{\partial y_1}(x_1,0;\xi,0)\right\}ds\right]y_1\end{aligned} \tag{12}$$

**Asymptotical match of inner and outer problems**

The unknown source strength $\sigma$ and vortex strength $\gamma$ 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 $\Phi$ and $\phi$ that have similar nature, the following integral equation for $\gamma$ can be obtained:

$$\frac{1}{c(x_1)}\int_{x_1}^{\frac{L}{2}}\gamma(\xi,t)d\xi-\frac{1}{\pi}\int_{L_jw_j}\gamma(s,t)\left[\frac{1}{x_1-\xi}+\frac{\partial H^{(\gamma)}}{\partial y_1}(x_1,y_0;\xi,\eta)\right]d\xi=-\frac{U}{2\pi H}\int_{-\frac{L}{2}}^{\frac{L}{2}}S'(\xi)\frac{\partial H^{(\sigma)}}{\partial y_1}(x_0,y_0;\xi,\eta)d\xi \tag{13}$$

The hydrodynamic forces acting on ship can be obtained by solving this integral equation for $\gamma$. The solution $\gamma$ of equation (13) should satisfy the additional conditions:

$$\gamma(x_1,t)=\gamma(x_1)\ \text{ for } x_1<-\frac{L}{2},\ \int_{-\infty}^{\frac{L}{2}}\gamma(\xi,t)d\xi=0,\ \gamma\left(x_1=-\frac{L}{2},t\right)=-\frac{1}{U}\frac{d\Gamma}{dt} \tag{14}$$

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

$$F(t)=-h\int_{-\frac{L}{2}}^{\frac{L}{2}}\Delta P(x_1,t)dx_1,\ M(t)=-h\int_{-\frac{L}{2}}^{\frac{L}{2}}x_1\Delta P(x_1,t)dx_1 \tag{15}$$

where $\Delta P$ 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

$$C_F=\frac{F}{\frac{1}{2}\rho LdU^2},\ C_M=\frac{M}{\frac{1}{2}\rho L^2dU^2} \tag{16}$$

where, $L$ is the ship length and $d$ is the draft of ship. $\rho$ is the water density.

## PREDICTION OF HYDRODYNAMIC INTERACTION BETWEEN SHIP AND WEDGE-SHAPED BANK

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 $\beta$ have been examined. A parametric study on the numerical calculations has been conducted on VLCC 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 4 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 3.0 times of a ship draft under the condition of 4 kt in ship velocity, respectively. Moreover, in order to calculate hydrodynamic interaction due to shape of the side walls, angle $\beta$ has changed to 10, 45, 90, 135, and 180 degrees.

Table 1 Principal particulars.

| | VLCC |
|---|---|
| $L(m)$ | $320m$ |
| $B(m)$ | $58m$ |
| $d(m)$ | $19.3m$ |
| Block Coefficient | 0.8018 |

Figure 2 and figure 3 show the hydrodynamic forces and moments from side walls when large vessel pertaining low speed of 4kt passes near wedge-shaped bank of angle at 45 degrees of $\beta$ and water depth to draft ratio of 1.3 ($h/d = 1.3$). Calculations in these figures were made by changing horizontal direction between the vessel and wedge-shaped bank of angle from 0.1 times to 0.5 times of ship length. Observing the characteristics of hydrodynamic force and moment between side wall and vessel in figure 2 and figure 3, its qualitative characteristics are similar in considering different distances, but its quantitative charac-teristics differ; when the spacing between ship and bank is less than about 0.2 times of ship length, hydrodynamic interaction dramatically increases, and when spacing is more than about 0.3 times, hydrodynamic interaction reversely decreases. Also it can be inferred from the calculation result when the spacing between ship and bank is half the size of ship length, hydrodynamic interaction almost diminishes.

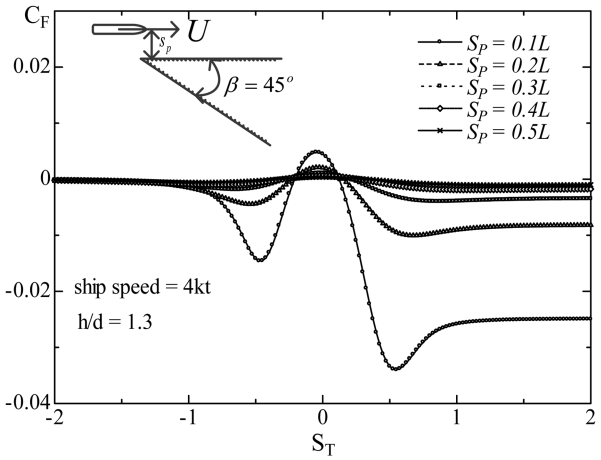

Fig. 2 Computed hydrodynamic forces acting on a ship passing by a wedge-shaped bank.

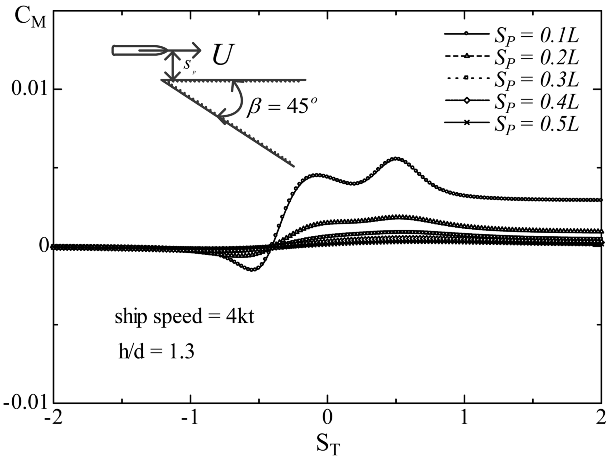

Fig. 3 Computed hydrodynamic moments acting on a ship passing by a wedge-shaped bank.

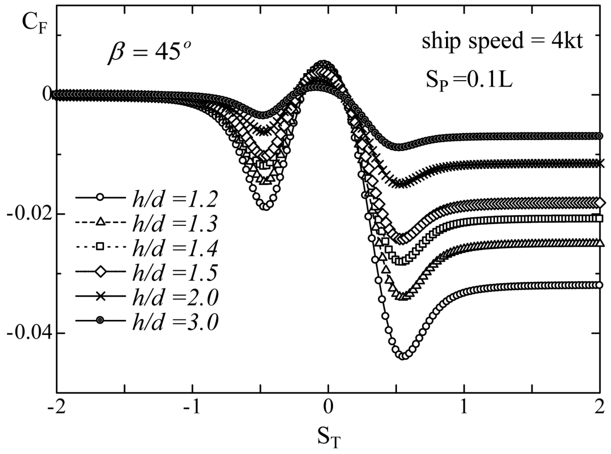

Fig. 4 Computed hydrodynamic forces acting on a ship passing by a wedge-shaped bank for different water depth.

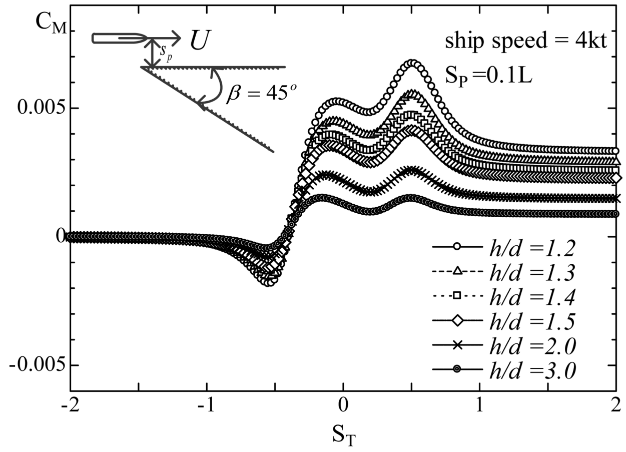

Fig. 5 Computed hydrodynamic moments acting on a ship passing by a wedge-shaped bank for different water depth.

Figure 4 and figure 5 show hydrodynamic forces and moments from side walls when ship by setting water depth and vessel draft ratio as variable in condition of 45 degrees of β and lateral distance between ship and wedge-shaped bank of angle of 0.1 times of the ship length. In this case, water depth to draft ratio (*h*/*d*) was set to 1.2, 1.3, 1.4, 1.5, 2.0, and 3.0 in order to calculate. By the calculation results from figure 4 and figure 5, it can be inferred that similar charac-teristics are present qualitatively regardless of the water depth to draft ratio, but in quantitative characteristics, when water depth to draft ratio (*h*/*d*) is lower than 2.0 hydrodynamic forces significantly increases as water depth decreases. On the other hand, when the vessel passes in slow speed and the variables are more than 2.0, bank effect significantly decreases as water depth increases.

Figure 6 and figure 7 show the hydrodynamic forces and moments from side walls when large vessel with low speed of 4kt passes near wedge-shaped bank of angle at 135 degrees of β and water depth to draft ratio of 1.3 ($h/d = 1.3$). Calculations in these figures were made by changing horizontal direction between the vessel and wedge-shaped bank of angle from 0.1 times to 0.5 times of ship length. Observing the characteristics of hydrodynamic force and moment between side wall and vessel in figure 6 and figure 7, almost identical to figure 2 and figure 3, its qualitative charac-teristics are similar in considering different distances, but its quantitative characteristics differ; when the spacing between ship and bank is less than about

0.2 times of ship length, hydrodynamic interaction dramatically increases, and when spacing is more than about 0.3 times of ship length, hydrodynamic interaction dramatically decreases. Also it can be inferred from the calculation result when the spacing is half the size of ship length, bank effect almost diminishes. In conclusion inferred from figure 2, 3 and 6, 7, when the space between slow vessel and wedge-shaped bank of angle is about 0.5 times of ship length regardless of angle, the hydrodynamic force acted on ship almost diminishes.

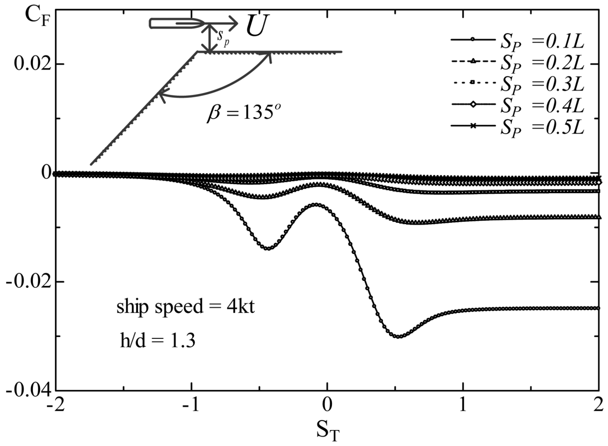

Fig. 6 Computed hydrodynamic forces acting on a ship passing by a wedge-shaped bank.

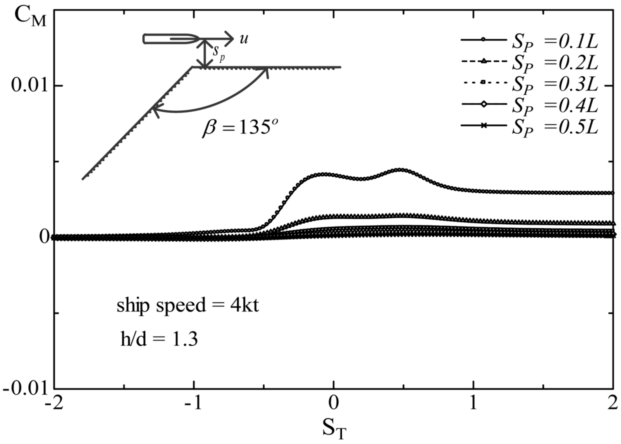

Fig. 7 Computed hydrodynamic moments acting on a ship passing by a wedge-shaped bank.

## RESULTS AND DISCUSSION

This section presents quantitative and qualitative numerical calculation results from setting wedge-shaped bank of angle, water depth to draft ratio (*h*/*d*) as variable and changing the angle of the bank. Comparisons between the theoretical and experimental results for the case of $\beta$= 1 with various *h*/*d* are shown in figure 8 and figure 9.

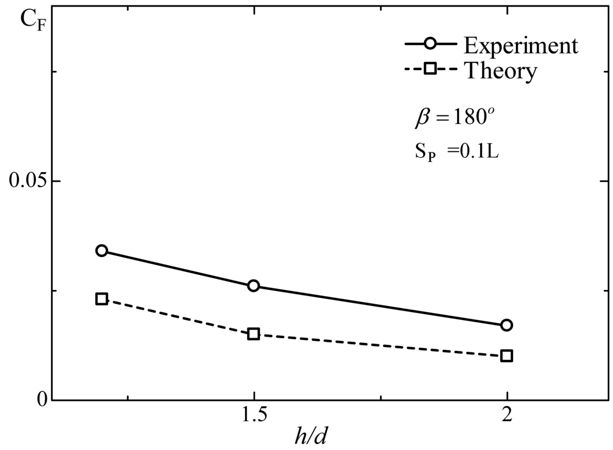

Fig. 8 Comparison of measured and calculated lateral force with function of *h*/*d*.

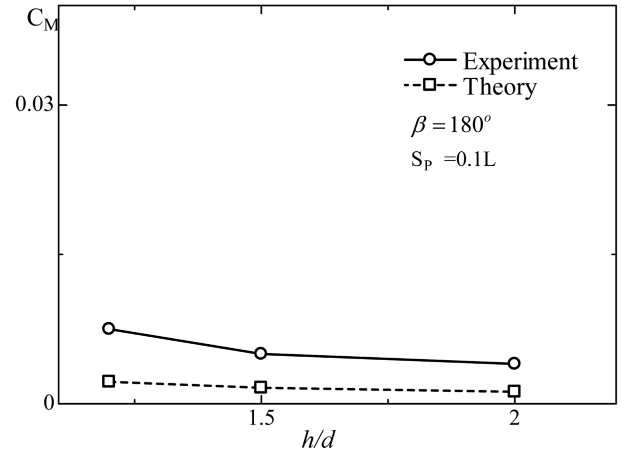

Fig. 9 Comparison of measured and calculated yaw moment with function of *h*/*d*.

As expected, some of the experimental results for the lateral forces and moments have a little difference, compared to the cases of theoretical results. This is probably the result of viscous effects and the neglect of wave in the theory. However, the theoretical result for the forces and moments show good agreement in magnitude and tendency with experimental result when the model is in the far-field from the side wall (Lee, 2003). Characteristics obtained from the calculation results presented in figure 10 through 13, as water depth and the angle of the bank increases, hydrodynamic force and moment between vessel and bank significantly decreases. Also in condition of angle β from 10 degrees to 135 degrees, when water depth to

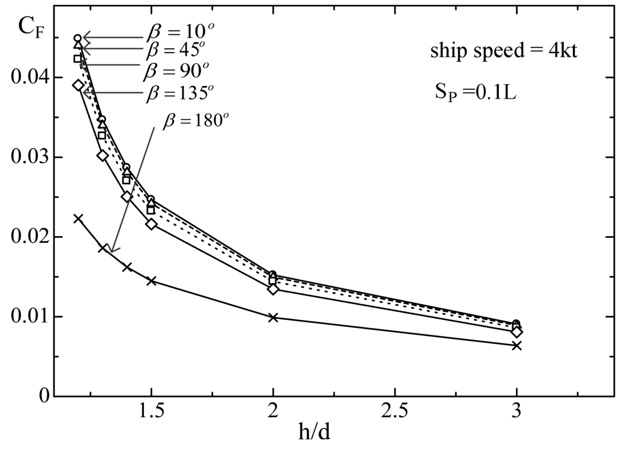

Fig. 10 Computed hydrodynamic forces acting on a ship passing by a wedge-shaped bank for different water depth and angle β.

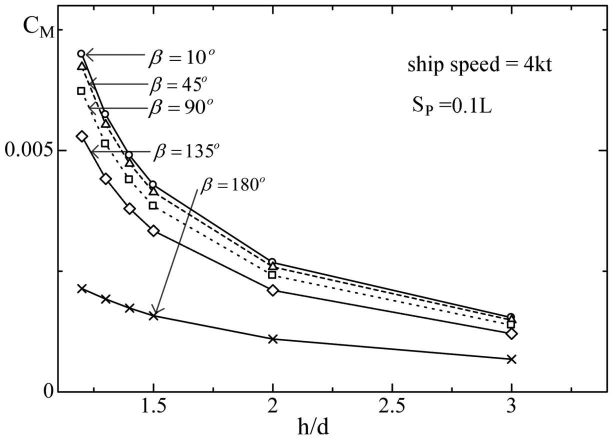

Fig. 11 Computed hydrodynamic moments acting on a ship passing by a wedge-shaped bank for different water depth and angle β.

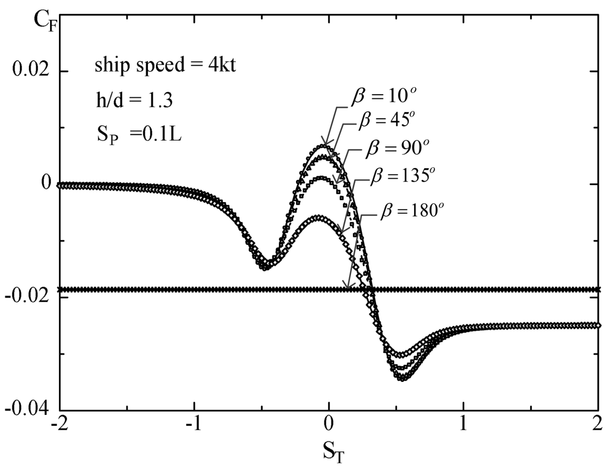

Fig. 12 Computed hydrodynamic forces acting on a ship passing by a wedge-shaped bank for different angle β.

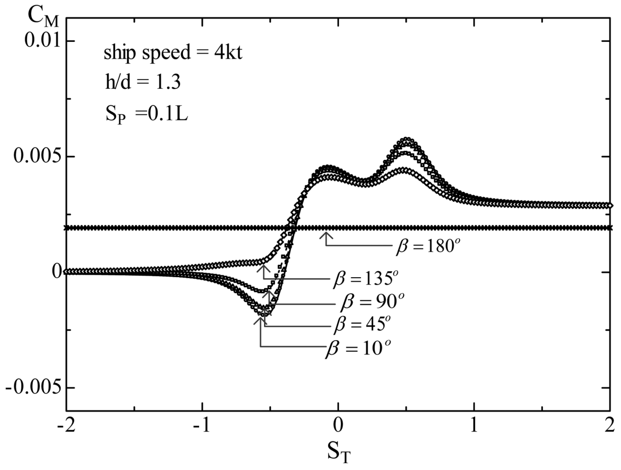

Fig. 13 Computed hydrodynamic moments acting on a ship passing by a wedge-shaped bank for different angle β.

draft ratio is lower than 2.0 ($h/d = 2.0$), the hydrodynamic force significantly increases as water depth decreases. On the other hand, when angle β is 180 degrees, hydrodynamic force slowly increases as water depth decreases.

## CONCLUSION

In this paper, the hydrodynamic interaction effect for the sake of reducing sea accidents in narrow waterways was determined by estimating interaction between wedge-shaped bank of angle and vessel, which is navigating through limited sea area such as narrow waterways. By calculating and analyzing its result, following conclusions were obtained.

First, based on slender body theory, hydrodynamic force and moment between vessel and side wall was obtained when setting water depth, angle of the wedge-shaped bank, and lateral distance between bank and the ship were set as variables.

Second, in case of hydrodynamic force and moment between wedge-shaped bank of angle and vessel, significant changes arose at the tip of wedge-shaped bank of angle, and as the angle increases the hydrodynamic force and moment decreases. This kind of influence will become a crucial factor for the ship's safe maneuvering controlling method.

Third, when passing at low speed of 4kt near the bank, the hydrodynamic force dramatically increases as the spacing between bank and vessel decreases when the lateral distance between bank and vessel is less than about 0.2 times of the ship length, and when lateral distance is more than about 0.3 times of the ship length, hydrodynamic interaction effect dramatically decreases as the lateral distance increases. Also when the lateral distance is about half length of the ship, influence from the bank almost diminishes.

Fourth, in case of this research, hydrodynamic interaction effect dramatically increases as water depth decreases when water depth to draft ratio ($h/d$) is lower than 2.0, and the hydrodynamic interaction effect slowly decreases as water depth increases when $h/d$ is more than 2.0.

In conclusion, calculation method and results suggested in this research will be convenient to be used for constructing a traffic safety system of ships maneuvering near the narrow waterways, such as avoiding crashing accidents, constructing an automatic controlling system, making an ocean traffic control system, and building safe harbors.

## ACKNOWLEDGEMENTS

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