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Int. J. Nav. Archit. Ocean Eng. (2015) 7:691~698
http://dx.doi.org/10.1515/ijnaoe-2015-0048
pISSN: 2092-6782, eISSN: 2092-6790

Numerical analysis for hydrodynamic interaction effects between vessel and semi-circle bank wall

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Received 17 June 2013; Revised 16 March 2015; Accepted 28 April 2015

ABSTRACT: *The hydrodynamic interaction forces and moments induced by the vicinity of bank on a passing vessel are known as wall effects. In this paper, the characteristics of interaction acting on a passing vessel in the proximity of a semi-circle bank wall are described and illustrated, and the effects of ship velocity, water depth and the lateral distance between vessel and semi-circle bank wall are discussed. For spacing between ship and semi-circle bank wall (SP) less than about 0.2 L and depth to ship's draft ratio (h/d) less than around 2.0, the ship-bank interaction effects increase steeply as h/d decreases. However, for spacing between ship and semi-circle bank wall (SP) more than about 0.3 L, the ship-bank interaction effects increase slowly as h/d decreases, regardless of the water depth. Also, for spacing between ship and semi-circle bank wall (SP) less than about 0.2 L, the hydrodynamic interaction effects acting on large vessel increase largely as ship velocity increases. In the meantime, for spacing between ship and semi-circle bank wall (S_P) more than 0.3 L, the interaction effects increase slowly as ship velocity increases.*

KEY WORDS: Interaction effect; Wall effect; Spacing between vessel and semi-circle bank wall; Ship velocity; Water depth.

NOMENCLATURE

B	Breadth of ship
C_F , C_M	Dimensionless hydrodynamic force and yaw moment of ship
d	Draught of ship
ε	Slenderness parameter
Φ	Velocity potential
h	Water depth
$H^{(\sigma)}, H^{(\gamma)}$	Functions on the bank wall
L	Ship length
ΔP	Difference of linearized pressure about x_1 -axis
σ, γ	Source and vortex strength
ξ, η	Source and vortex point
S_P, S_T	Lateral and longitudinal distance between ship and wedge-shaped bank
U	Ship velocity

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INTRODUCTION

During the last decades a continuous increase in speed and size of modern vessels makes their consideration in the design of channels, canals and ports. However, the dimensions of access canals, channels and ports frequented by these vessels often do not increase at the same rate. So, the problem of ship controllability in confined waters due to the effect of shallow water or inherently restricted nature of waterways is the main concern not only of naval architects and ship operators but also of engineers who will design future waterways. In general, the asymmetric flow around a vessel induced by the vicinity of banks causes pressure differences between starboard and port sides when a vessel is approached toward the bank in confined waters, such as near some fixed obstacles, or in a narrow channel. This phenomenon is known as bank effect and depends on many parameters, including the bank shape, depth, the spacing between vessel and bank, and ship velocity. Also, the bank effect has a significant impact on the maneuvering characteristics of the vessel, and the hydrodynamic force and moment between large vessel and bank can't be neglected from the viewpoint of marine disasters. For this to be possible, the hydrodynamic interaction effects between large vessel and restricted waters should be well understood, and the research on this field has been reported for the past years. Newman (1965; 1969; 1972) reported the force and moment between vessel and bank based on the slender body and some theory for ship maneuvering. Also, similar work was reported by Davis (1986), Norrbin (1974), Yeung and Tan (1980), Kijima et al. (1991) and Yasukawa (2002a) studied the hydrodynamic interaction forces and moments between vessels in the proximity of a bank wall. Kijima and Qing (1987), Kijima and Furukawa (1994), Yasukawa (1991), Yasukawa (2002b) investigated the bank effect on ship maneuvering motions in the proximity of bank or in a channel with varying width. Also, Lee and Lee (2008) analyzed the characteristic features of the hydrodynamic interaction effects between vessel and wedge-shaped bank of angle. Despite former studies, a detailed knowledge of the maneuvering characteristic safe ship operation between large vessel and bank or sidewall of the narrow channel is still being needed to prevent further marine accidents.

FORMULATION

Consider a slender vessel of length L moving parallel to one side of a semi-circle bank wall at a constant velocity U in an inviscid fluid of water 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 semi-circle bank wall. 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:

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

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

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

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

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

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.

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

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

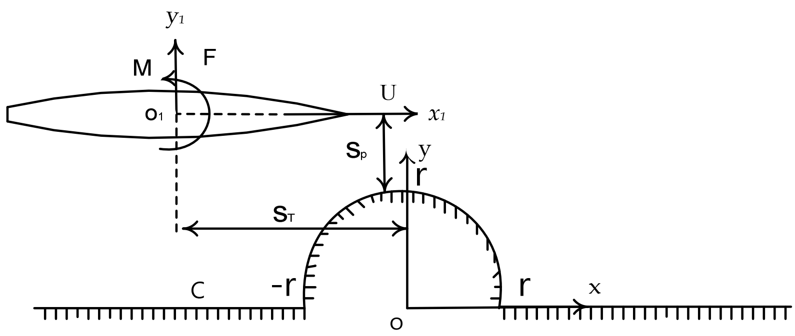

Fig. 1 Coordinate system.

Inner and outer solution

The inner region is defined by the following orders of magnitude of the coordinates: $x_1 = o(1), y_1 = z_1 = o(\varepsilon)$. The outer expansion in an outer region is defined by the following orders of magnitude of the coordinates: $x_1 = y_1 = o(1), z_1 = o(\varepsilon)$. 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):

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

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 (Kijima et al., 1991):

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

where $\sigma(s,t)$ and $\gamma(s,t)$ are the source and vortex strengths, respectively. L and w denote the flow field along the large vessel and vortex wake shed behind the vessel, respectively. ξ and η represent the source and vortex point. $H^{(\sigma)}$ and $H^{(\gamma)}$ are green functions satisfying the semi-circle bank wall and ds is an infinitesimal arc-length element along the ship's axis.

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 (Kijima et al., 1991):

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

where the blockage coefficient $C(x_1)$) of a vessel in shallow water is a hydrodynamic constant and is dependent on the shape of vessel and water depth Taylor (1973). The hydrodynamic forces acting on a ship can be obtained by solving this integral equation for γ . The solution γ of Eq. (8) should satisfy the additional conditions:

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

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

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

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 vessel is given by

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

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

PREDICTION OF HYDRODYNAMIC INTERACTIONS BETWWEN VESSEL AND SEMI-CIRCLE BANK WALL

In this section, the hydrodynamic forces acting on a vessel while approaching and moving parallel to one side of a semi-circle bank wall 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 semi-circle bank wall was investigated as shown in Fig. 1. If the speeds of ship (denoted as U) are varied, such as 2 *kts*, 4 *kts*, 6 *kts* and 8 *kts*, respectively, and the spacing between ship and semi-circle bank wall varies, such as 0.1, 0.2, 0.3, 0.4 times of the ship length. Also, the water depth was chosen to be 1.2 to 3.0 times of a ship draft. In addition, the radius of semi-circle bank wall is varied, such as 30 *m*, 50 *m*, 70 *m* and 100 *m* respectively.

Table 1 Principal particulars.

	VLCC
L (m)	325 *m*
B (m)	53 *m*
d (m)	22.05 *m*
Block coefficient (C_B)	0.831

Figs. 2 and 3 show the calculated hydrodynamic forces and moments between large vessel and semi-circle bank wall when the vessel pertaining low speed of 2 *kts* passes near the semi-circle bank wall and water depth to draft ratio of 1.3 (h/d=1.3). In this case, the radius of semi-circle bank was set to 30 *m*, 50 *m*, 70 *m* and 100 *m* in order to calculate under the condition of S_p =0.1 *L*. Observing the characteristics of hydrodynamic interaction between ship and semi-circle bank wall in these figures, its quailtative characteristics are similar in considering different radius, but its quantitative characteristics differ.

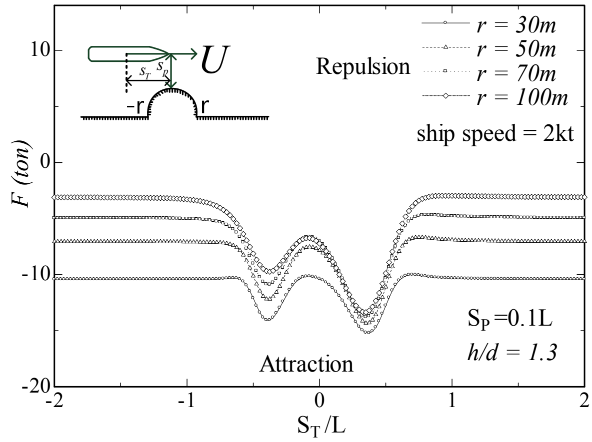

Fig. 2 Calculated hydrodynamic forces acting on a ship passing by a semi-circle bank wall.

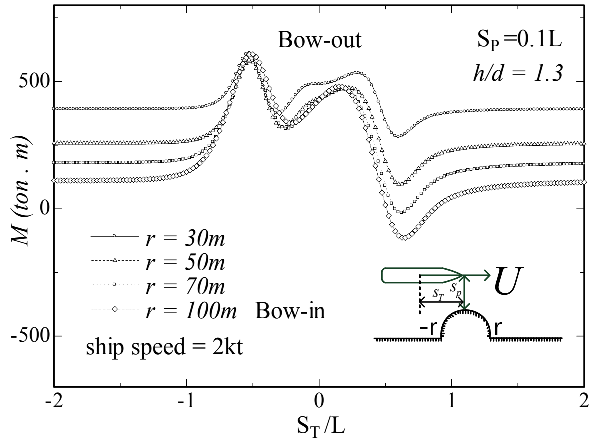

Fig. 3 Calculated hydrodynamic moments acting on a ship passing by a semi-circle bank wall.

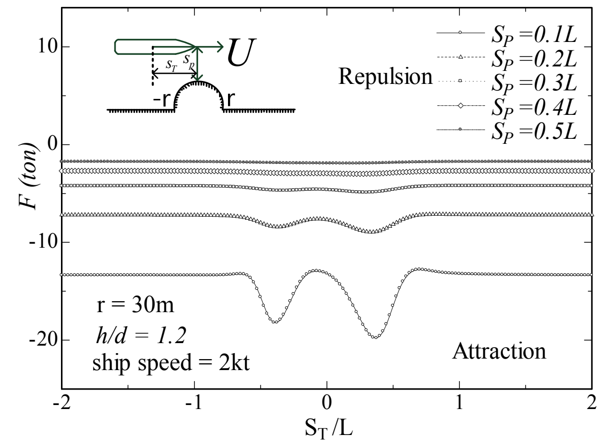

Fig. 4 Calculated hydrodynamic forces acting on a ship passing by a semi-circle bank wall for different lateral distance.

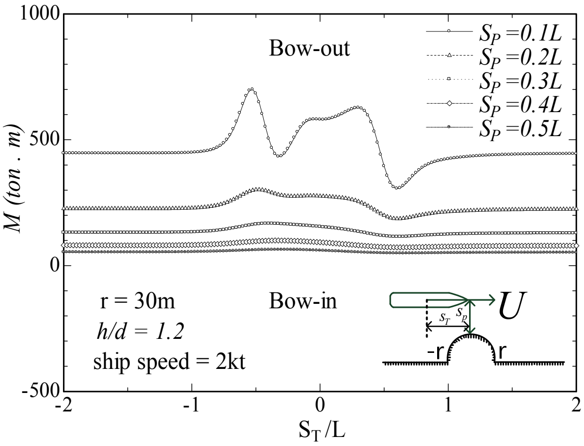

Fig. 5 Calculated hydrodynamic moments acting on a ship passing by a semi-circle bank wall for different lateral distance.

Figs. 4 and 5 show the computed hydrodynamic forces and moments from semi-circle bank wall when the vessel pertaining low speed of 2 *kt* asses near the bank and water depth to draft ratio of 1.2 (h/d=1.2). Calculations in these figures were made by changing horizontal direction between the ship and semi-circle bank wall from 0.1 times to 0.5 times of ship length. Observing the characteristics of ship-bank wall interaction effect in these figures, its qualitative characteristics are similar in considering different lateral distances, but its quantitative characteristics differ; when the lateral distance between ship and semi-circle bank wall is less than about 0.2 times of ship length, ship-bank interaction effect sharply increases, and when lateral distance is more than about 0.3 times of ship length, ship-bank interaction effect largely decreases. Furthermore, it can be inferred from the calculation result when the lateral distance between ship and semi-circle bank wall is about 0.5 times of ship length, ship-bank interaction effect almost disappeared.

Figs. 6 and 7 display the computed hydrodynamic forces and moments from semi-circle bank wall when ship by setting water depth and draft ration as variable in condition of 2 *kts* of ship velocity and spacing between ship and semi-circle bank wall of 0.1 times of the ship length. In this case, water depth to draft ratio (h/d) was set to 1.2, 1.5, 2.0, 2.5 and 3.0 in order to calculate. By the calculation results from these Figs. 6 and 7, it can be inferred that similar characteristics are present qualitatively regardless of the water depth to draft ratio, but its quantitative characteristics differ; when water depth to draft ratio is less than around 2.0, ship-bank interaction effect largely increases as water depth decreases, and when the vessel passes in low speed of 2 *kts* and h/d is more than about 2.0, ship-bank interaction effect significantly decreases as water depth increases.

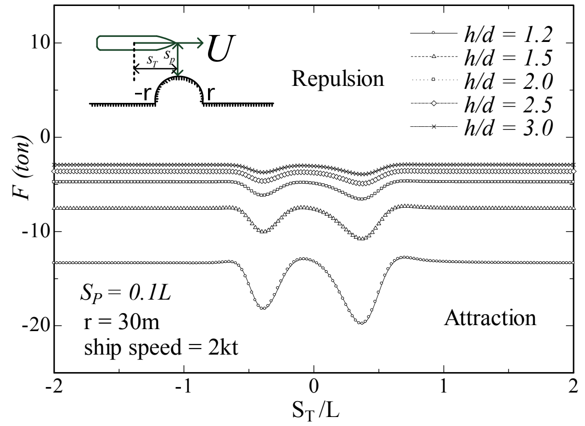

Fig. 6 Calculated hydrodynamic forces acting on a ship passing by a semi-circle bank wall for different water depth.

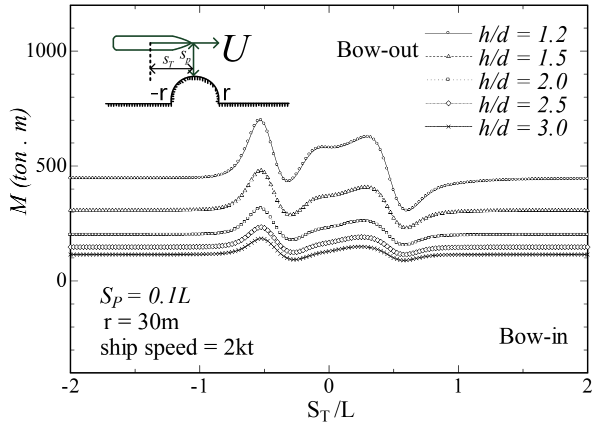

Fig.7 Calculated hydrodynamic moments acting on a ship passing by a semi-circle bank wall for different water depth.

RESULTS AND DISCUSSION

Figs. 8 and 9 show the calculated hydrodynamic interaction effects between large vessel and semi-circle bank wall for different lateral distance and water depth. In these figures, ship-bank hydrodynamic force and moment acting on a vessel passing by a semi-circle bank wall become larger as water depth decreases, compared to the case of deep water depth. For spacing between ship and semi-circle bank wall (S_P) less than about 0.2 L and water depth to draft ratio (h/d) less than around 2.0, the hydrodynamic interaction forces and moments increase dramatically as h/d decreases. On the other hand, when the lateral distance between ship and semi-circle bank wall is more than about 0.3 times of ship length, the ship-bank interaction effects increase slowly as h/d decreases, regardless of the water depth. In particular, for spacing between large vessel and semi-circle bank wall (S_P) less than about 0.1 L and water depth to draft ratio (h/d) less than about 1.5, the semi-circle bank wall generates the largest disturbance. It is found that there is a dangerous tendency to force the stern of the ship passing towards the radius of semi-circle bank wall after the ship has just passed the leading part of the semi-circle bank wall.

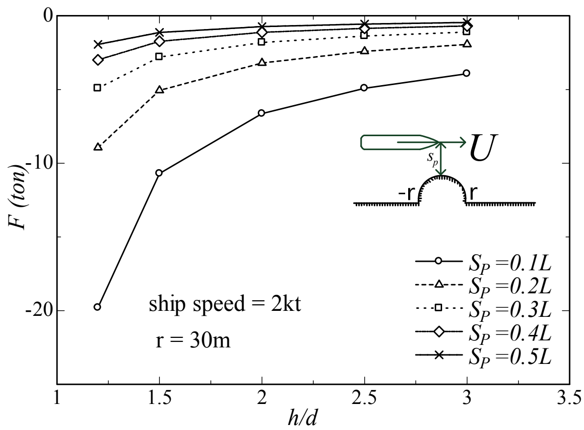

Fig. 8 Calculated hydrodynamic forces acting on a ship passing by a semi-circle bank wall for different lateral distance and water depth.

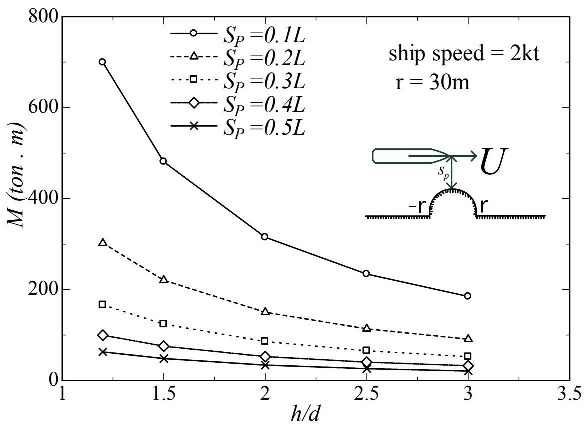

Fig. 9 Calculated hydrodynamic moments acting on a ship passing by a semi-circle bank wall for different lateral distance and water depth.

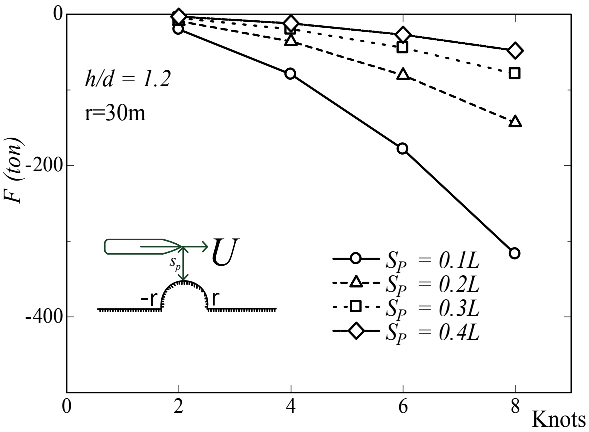

Fig. 10 Calculated hydrodynamic forces acting on a ship passing by a semi-circle bank wall for different ship velocity.

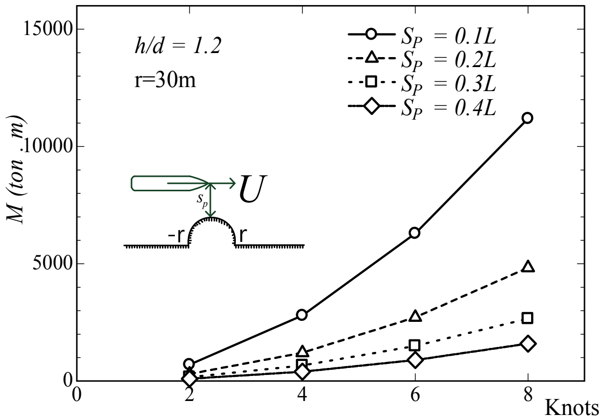

Fig. 11 Calculated hydrodynamic moments acting on a ship passing by a semi-circle bank wall for different ship velocity.

Also, Figs. 10 and 11 show the computed ship-bank interaction effects for different lateral distance and ship velocity. In this case, the speeds of vessel are varied, such as 2 *kt*, 4 *kt*, 6 *kt* and 8 *kt*, respectively, and also the calculations in these figures were made by changing horizontal direction between the ship and semi-circle bank wall from 0.1 times to 0.4 times of ship length. In Figs. 10 and 11, for spacing between ship and semi-circle bank wall (S_P) less than about 0.2 *L*, the hydrodynamic interaction forces and moments acting on a vessel increase sharply as ship velocity increases. In the meantime, when the lateral distance between ship and semi-circle bank wall is more than about 0.3 times of ship length, the ship-bank interaction effects increase slowly as ship velocity increases. In particular, as expected, for spacing between ship and semi-circle bank wall (S_P) less than about 0.1 *L*, the hydrodynamic interaction forces and moments acting on a vessel increase dramatically as ship velocity increases. Characteristics obtained from the calculation results presented in Fig. 8 through Fig. 11, ship-bank interaction effects significantly increases, as water depth and spacing between ship and semi-circle bank wall decreases.

CONCLUSION

In this research, ship-bank interaction effect for the sake of reducing marine accidents in restricted waters was determined by estimating hydrodynamic force and moment between semi-circle bank wall and vessel, which is moving through limited sea area such as narrow channels. From the above numerical analysis, the following conclusions can be drawn.

First, in case of interaction effect between ship and semi-circle bank wall, significant changes arose at the leading part of radius of semi-circle bank wall, as the radius increases the semi-circle bank wall generates the largest disturbance.

Second, when moving at low speed of 2 *kt* near the semi-circle bank wall, the interaction effect sharply increases as the lateral distance between ship and bank decreases when the spacing between ship and bank is less than about 0.2 times of ship length, and when spacing is more than about 0.3 times of ship length, the interaction effect largely decreases as the lateral distance increases. Furthermore, when the lateral distance is about 0.5 times of ship length, the influence from the semi-circle bank wall almost disappeared.

Third, for spacing between ship and semi-circle bank wall less than about 0.2 *L*, the hydrodynamic interaction forces and moments increase sharply as h/d decreases when water depth to draft ratio is less than about 2.0. However, when the spacing between ship and semi-circle bank wall is more than about 0.3 *L*, the ship-bank interaction effects increase slowly as h/d decreases. In particular, for spacing between ship and semi-circle bank wall less than about 0.1 *L*, the interaction effect increases dramatically as h/d decreases when h/d is less than about 1.5.

Fourth, as expected, when the lateral distance between ship and semi-circle bank wall is less than about 0.1 *L*, the interaction effects acting on a vessel increase sharply as ship velocity increases.

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