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# Research and application on numerical simulation of ship maneuvering motion under bank effect

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**Abstract.** A ship maneuvering mathematical model was established considering the influence of river bank effect based on the depth integrated 2-D flow mathematical model. Taking the section of the Suoluo beach reach of Lancang River in Yunnan Province as an example, the numerical simulation of ship maneuvering motion under bank effect was carried out. Results show that the typical ship can not ascend rapids when considering the bank effect, so it is necessary to implement channel regulation. The study reveals that the model can simulate the ship maneuvering motion and navigation status under bank effect, which can provide some useful references for the ship's navigation and maneuvering in mountainous rivers.

## 1. Introduction

With the rapid development of Chinese shipping industry, the numerical simulation of ship maneuvering motion is more and more widely used in port channel, inland waterway and other aspects of ship maneuvering performance and navigation safety[1-3]. However, there is little research on ship model for mountains waterway. The mountainous waterway has characteristics of steep gradients, narrow river surface and high flow velocities, which has a serious impact on navigation safety of ships. When a ship sails in a mountainous waterway, it is prone to have a bank effect between the ship and banks. The bank effect refers to the phenomenon that the bow is pushed away from the bank and the stern is drawn to the shore when a ship is sailing or berthing in a narrow channel[4]. This phenomenon is harmful to navigation safety and easily leads to navigation accidents. Therefore, it is necessary to study the ship maneuvering motion under bank effect.

Bank effect to ship maneuvering motion can be carried out through physical model or mathematical model. Many scholars have derived many empirical formulas through physical experiments[5-8]. However, these kinds of formulas have some limitations for complex navigation environment and ships of different sizes. At present, the common research method is the mathematical model method. The results of mathematical model are more convenient and reliable than physical model, but seldom research was put on the numerical simulation of ship maneuvering motion under bank effect. In this paper, based on the depth integrated 2-D flow mathematical model, the flow field of Suoluo beach reach of Lancang River in Yunnan Province is calculated. By using the mathematical model of ship maneuvering motion under bank effect, the ship's self-propelled landing on the beach under different conditions of bank effect was simulated, and the navigation parameters are compared and analyzed.



Results show that the ship can ascend rapids without considering bank effect, while the ship can not ascend rapids under bank effect. Therefore, the relevant channel regulation should be carried out for the reach with bank effect to ensure the safety and stability of navigation.

## 2. Ship maneuvering mathematical model

### 2.1. Fundamental equation

In this paper, a ship maneuvering mathematical model was developed based on the depth integrated 2-D flow mathematical model[9]. The establishment and verification of the model refer to the research done by Tang Xiao'ya et al[10]. The actual movements of a ship generally have six degrees of freedom, which are yawing, surging, swaying, heaving, pitching and rolling. In this paper, three degrees of freedom including yawing, surging and swaying were studied in rectangular coordinate system( $x_0y_0$ ) of the plane two-dimensional flow. According to Newton second law, this motion of a ship can be described by the following formation.

$$X_0 = m\ddot{x}_{0G}, Y_0 = m\ddot{y}_{0G}, N = I_z\ddot{\psi} \quad (1)$$

where  $X_0$  and  $Y_0$  are the component force of resultant force acting on the ship in  $x_0$ -axis and  $y_0$ -axis directions respectively,  $N$  is the moment of resultant force about the vertical axis of the ship center of gravity,  $m$  is the mass of the ship,  $\psi$  is the bow angle of the ship,  $x_{0G}$  and  $y_{0G}$  are the coordinates of ship center of gravity at time  $t_0$ , and  $I_z$  is the mass moment of inertia of the ship around the  $z$ -axis.

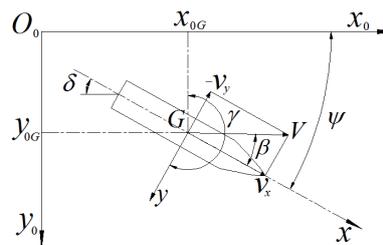


Figure 1. Coordinate system of ship maneuvering motion.

### 2.2. Ship maneuvering motion equation

#### 2.2.1. Ship motion equation in still water

In order to simplify calculation, an independent coordinate system is usually adopted, that is, the origin is center of the ship, the  $x$ -axis is the direction of the ship's bow and stern, and the  $y$ -axis is the vertical direction of the ship's bow and stern. The still-water ship motion equation is as follows:

$$X = (m + m_{11})v'_x - (m + m_{22})v_y r, Y = (m + m_{22})v'_y + (m + m_{11})v_x r, N = (I_z + m_{33})r' \quad (2)$$

where  $v_x$  and  $v_y$  are the relative velocities of the hull and the flow in  $x$  and  $y$  directions,  $r$  is the bow angular velocity,  $X$  and  $Y$  are the components of the resultant force acting on the ship in  $x$ -axis and  $y$ -axis directions respectively,  $N$  is the moment of the resultant force about the vertical axis of the ship center of gravity,  $m_{11}$ ,  $m_{22}$  and  $m_{33}$  are the additional masses and additional inertia moments in  $x$ ,  $y$  and  $z$  directions, and other symbols as before.

#### 2.2.2. Ship motion equation in dynamic-water

$$\begin{cases} (m + m_{11})u'_x = X(v_x, v_y, r) + (m + m_{22})v_y r + (m + m_{11})V_F r \sin(\psi_F - \psi) \\ (m + m_{22})u'_y = Y(v_x, v_y, r) - (m + m_{11})v_x r - (m + m_{22})V_F r \cos(\psi_F - \psi) \\ (I_z + m_{33})r' = N(v_x, v_y, r) \end{cases} \quad (3)$$

where  $V_F$  and  $\psi_F$  are the absolute velocity and direction of flow respectively,  $u_x$  and  $u_y$  are origin velocity of moving coordinates,  $v_x$  and  $v_y$  are the velocities of a ship relative to water in  $x$  and  $y$  directions, and  $u_{cx}$  and  $u_{cy}$  are the flow velocities in  $x$  and  $y$  directions.

### 2.3. Hydrodynamic expression

The commonly used hydrodynamic model expresses  $X$ ,  $Y$  and  $N$  as follows:

$$\begin{cases} X = X_H(v_x, v_y, r) + X_R(v_x, v_y, r) + X_P(v_x, v_y, r) + X_W + X_{WV} \\ Y = Y_H(v_x, v_y, r) + Y_R(v_x, v_y, r) + Y_P(v_x, v_y, r) + Y_W + Y_{WV} \\ N = N_H(v_x, v_y, r) + N_R(v_x, v_y, r) + N_P(v_x, v_y, r) + N_W + N_{WV} \end{cases} \quad (4)$$

where the subscripts  $H$ ,  $R$ ,  $P$ ,  $W$  and  $WV$  denote the force and moments acting on the bare hull, rudder and propeller, and generated by wind and wave respectively. Considering that the transverse force and moment caused by propeller are usually small, it is difficult to measure and separate them from the measurement, so they are usually combined.

### 2.4. Ship motion equation considering bank effect

The regression formula of shore suction and shore pushing moment, which was derived by Ch'ng[11] and others through the ship pool test, was taken as the ship maneuvering motion equation based on the bank effect. The formula has been applied to the simulator of Shanghai Maritime University and widely verified in production practice[12].

$$Y_s = 0.001 \cdot (0.5 \rho V^2 L^2) \{a_5 y_{B3} |y_{B3}| F_n + a_7 y_{B3} [d / (h-d)] + a_9 y_{B3} F_n [d / (h-d)] + a_{13} y_{B3} [d / (h-d)]^2\} + \delta Y \quad (5)$$

$$\begin{aligned} N_s = 0.001 \cdot (0.5 \rho V^2 L^3) \{ & b_8 y_{B3} |y_{B3}| [d / (h-d)] + b_{13} y_{B3} [d / (h-d)]^2 \\ & + b_{14} y_{B3} |y_{B3}| [d / (h-d)] + b_{16} y_{B3} F_n^2 [d / (h-d)]^2\} + \delta N \end{aligned} \quad (6)$$

$$\delta Y = 0.001 \cdot (0.5 \rho V^2 L^2) \{0.11 y_B C_T [d / (h-d)] + 0.0006 y_B C_T^2 [d / (h-d)]^2\} \quad (7)$$

$$\delta N = 0.001 \cdot (0.5 \rho V^2 L^3) \{0.0009 y_B C_T^2 [d / (h-d)] - 0.0044 y_B |y_B| C_T^2 [d / (h-d)]\} \quad (8)$$

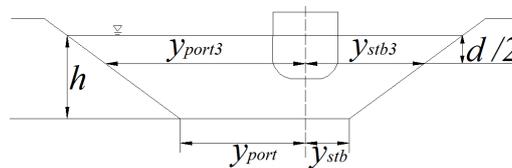


Figure 2. Sketch of typical cross section.

where  $V$  is the ship velocity,  $L$  is the ship length,  $F_n$  is the Froude number,  $h$  is water depth,  $d$  is the ship draft,  $y_{port}$  and  $y_{stb}$  are the distances from the center of the ship to the left and right bank at the bottom of the water,  $y_{port3}$  and  $y_{stb3}$  are the distances between the center of the ship and the left and right bank at half of the draft, and the cross section shape and parameters of the bank are shown in figure 2; where  $C_T$  is the thrust coefficient, and the calculation formula is  $C_T = T_p / \{0.5 \rho D_p^2 [V(1 - \omega_p)]^2\}$ .

### 2.5. Solutions of ship maneuvering motion equations

Ship maneuvering motion equations are ordinary differential equations with first order derivative, which are extremely complex to solve. It is very reliable to use Runge-Kutta method to solve these equations. The equations of ship positions and relevant parameters at any time can be obtained by solution.

$$\begin{aligned} x_{i+1} &= x_i + (u_{xi} \cos \psi_i - u_{yi} \sin \psi_i) \Delta t, & y_{i+1} &= y_i + (u_{xi} \sin \psi_i + u_{yi} \cos \psi_i) \Delta t, & \psi_{i+1} &= \psi_i + r_i \Delta t \\ v_{x,i+1} &= u_{x,i+1} - V_F \cos(\psi_F - \psi_{i+1}), & v_{y,i+1} &= u_{y,i+1} - V_F \sin(\psi_F - \psi_{i+1}) \end{aligned} \quad (9)$$

### 2.6. Validation of the numerical model of ship maneuvering motion

The model selects Baoshou21 (52.6m×2.70m×1.95m) that is a 500t-class cargo ship as the representative ship, and carries out calculation and inspection on its performance (figure 3), that is to simulate the still-water direct navigation and turning ability(25° rudder angle) of the Baoshou21. It can be seen from figure 3 that the direct navigation performance of the ship is stable, and the turning

diameter( $D$ ) can meet the still-water turning diameter (1.5 ~ 3.5 times the ship length) of the various types of existing inland ships[13].

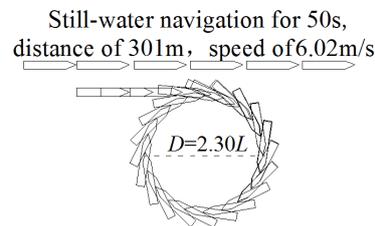


Figure 3. Characteristics of direct navigation and turning ability of typical ship.

### 3. Application of numerical simulation of ship maneuvering based on bank effect

#### 3.1. The reach survey

The selected reach is Suoluo beach reach of Lancang River in Yunnan Province, which belongs to the alluvial rapids of branch mouth in dry season. This reach is 2.8km downstream of Nanban estuary and 1.6km upstream of watermelon beach. This river section is straight and its shoreline is relatively smooth. The reach is relatively narrow with the width about 70m. The upper and lower sections of the reach are straight. A gully flows into the left bank of the middle section of the reach, and forms a shallow floodplain on the left bank. According to the measured data of the beach in May 2016, the maximum flow velocity is about 4.05m/s, which is located at the lower mouth of the impact reactor on right bank in the middle section. The maximum water surface gradient is about 7.8 ‰, which is located at upstream of the reach.

#### 3.2. Numerical simulation scheme

In this paper, the two-dimensional mathematical model of flow and the mathematical model of ship maneuvering motion are used to simulate the ship maneuvering under bank effect.

(1) Firstly, the actual flow field data of the selected river reach are obtained by 2D numerical simulation.

(2) Based on the flow field, the ship ascending rapids is simulated without considering the bank effect.

(3) Considering the bank effect.

#### 3.3. Numerical simulation results and analysis

Comparison of the self-propelled landing trajectories of 500t class cargo ship Baoshou21 considering or not considering the bank effect at the same rudder angle is shown in figure 4. It shows that the ship can ascend rapids smoothly without bank effect. However, after increasing bank effect, the ship suffered great resistance and finally stopped.

Through the comparison and analysis of the navigation trajectories and parameters of representative ships considering or not considering the bank effect at the same rudder angle, the ship trajectories are similar, and the changes of speed, drift angle and rudder angle are small. The ship which did not consider bank effect ascended rapids smoothly, but the ship considering bank effect had a greater resistance, stopped at the A-A section after sailing for 343s, and can't ascend rapids. The channel of this reach is narrow and has obvious bank effect, which has a great influence on ship navigation. Therefore, the bank effect can not be ignored, and it is necessary to regulate the channel.

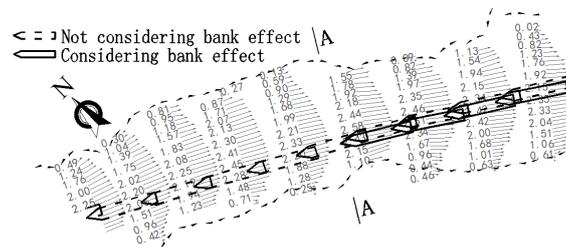


Figure 4. Comparison of ship trajectories by considering or not considering bank effect.

Table 1. Navigation parameters of a ship with different trajectories at the same rudder Angle(part).

Simulation conditions	Range (m)	Times (s)	Speed over bank( $\text{ms}^{-1}$ )	Drift angle( $^{\circ}$ )	Rudder angle( $^{\circ}$ )
<b>Not considering bank effect</b>	1533.1	400	3.28~4.84	-4.42~2.77	-6.00~2.00
<b>Considering bank effect</b>	570.8	143	0.50~4.52	-3.28~1.51	-2.00~2.00

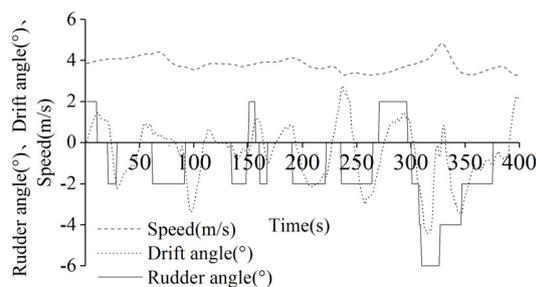


Figure 5. Navigation parameters of a ship(Part, Not considering bank effect).

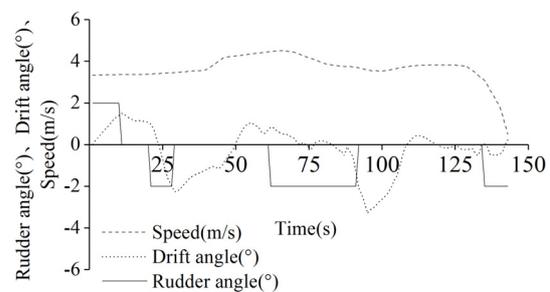


Figure 6. Navigation parameters of a ship(Part, Considering bank effect).

#### 4. Conclusions

(1) Based on the depth integrated 2-D flow mathematical model and the ship maneuvering motion model under the bank effect, this paper simulated the navigation trajectories of representative ships considering or not considering the bank effect, and obtained the corresponding speeds over bank, drift angles and rudder angles. Through the comparison and analysis of the trajectories and navigation parameters under different conditions, it is found that the bank effect has a great influence on the ship's navigation especially in mountainous rivers, which makes the ship unable to ascend rapids. Therefore, it is dangerous not to consider the bank effect when simulating the ship's ascending rapids in the mountainous channel. The simulation results provide a certain reference for mountainous waterway regulation and navigation of ships affected by the bank effect.

(2) The simulation results of ship maneuvering motion based on the bank effect show that the model is reliable, and can simulate the various navigation parameters of ships. The model can be applied to relative practical problems and has a friendly application prospect.

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