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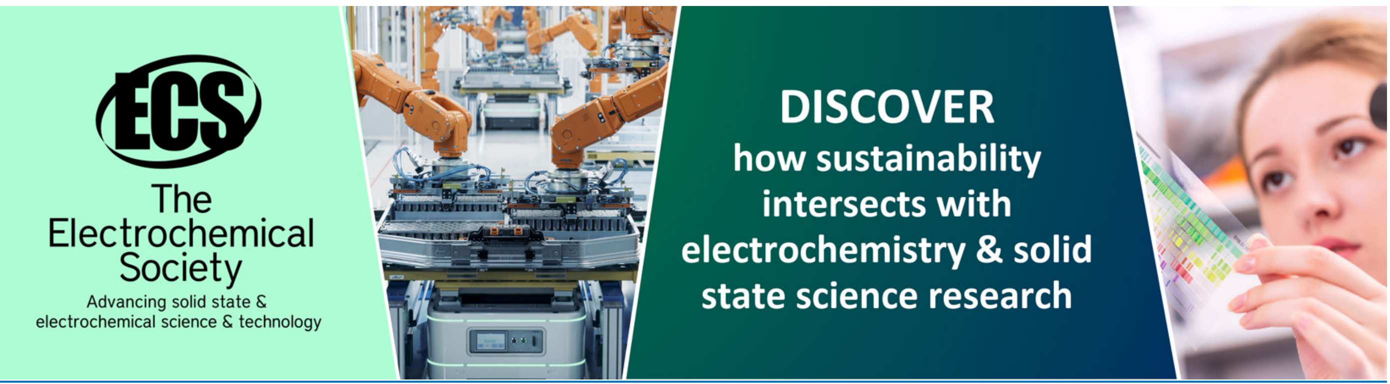

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Research and application of numerical simulation of ship maneuvering under non-uniform wind

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Abstract. Taking Fortran language as the platform, a depth-integrated two-dimensional non-uniform flow mathematical model and a ship maneuvering mathematical model were developed from the bottom layer. By further coupling the influence of wind, the mathematical model of ship maneuvering motion based on wind and current effects was constructed. Taking a typical river section in the Three Gorges Reservoir area as an example, the numerical simulation of ship maneuvering motion under still wind and non-uniform wind effect was carried out. Results show that the ships are obviously affected by wind in this river section. With the increasing change frequency of wind speed and direction, the difficulty of ship control increases correspondingly. In order to avoid the average accident, the ship must change its steer in time accordingly. This model can simulate the ship maneuvering motion and navigation status under wind effect quite well, which can provide some references for the ship's navigation and maneuvering in inland rivers.

1. Introduction

In addition to being affected by currents and its own power, it will also be affected by disturbances such as wind and waves when a ship navigates in rivers or oceans. If the wind speed is relevantly high and the wind direction changes, the maneuvering of the ship will become difficult and pose a great threat to the safety of navigation. At present, the numerical simulation of ship motion under wind effect is mainly focused on ports and ocean basins. The wind field data is mostly uniform wind and actual measurement data is often hard to achieved[1-2]. Few studies were put on the variations in the wind field of inland waterways[3-4].

The Three Gorges Reservoir reach is located in the upper reaches of the Yangtze River, which is an important part of Yangtze River shipping area. After the Three Gorges Dam is completed, the water level in front of the dam during the storage period increases from 135m to 175m, which widens the river and slows the water flow in the reservoir area and the navigation condition was greatly improved. However, the wind speed in the reservoir area is increasing after the impoundment of the Three Gorges Reservoir[5-6], and wind becomes a new factor affecting the navigation safety of ships. In order to ensure

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the navigation safety of ships in the reservoir area, the mathematical model of ship maneuvering motion under wind effect is developed based on the actual wind field data in the reservoir area. Navigation trajectory of ships under wind load is simulated and navigation parameters are analyzed and compared. Results show that this model can simulate the ship maneuvering motion under wind effect with efficiency, reliability, economy and convenience, which can provide some reference for related scientific research work.

2. Ship maneuvering mathematical model

The ship maneuvering mathematical model is established based on a depth-integrated two-dimensional mathematical flow model[7]. Cartesian coordinates system *(x_0Oy_0)* is adopted and the ship is regarded as a three-degree-of-freedom movement (yawing, surging and swaying) (figure 1). The motion of a ship can be described by the following formation.

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

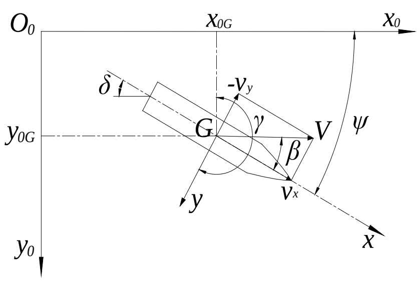

Fig. 1. Coordinate system of ship maneuvering motion

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, ψ is the bow angle of the ship, x_{0G} and y_{0G} are the coordinates of ship center of gravity at time t_0 respectively, and I_Z is the mass moment of inertia of the ship around the z-axis.

2.1. Ship motion equation

A moving ship is often regarded as an independent coordinate system (xGy), that is, an attached coordinate system. The origin point is located in the 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 and dynamic-water ship motion equation can be written as follows:

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

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

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, V_F and ψ_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.

2.2. Equation of wind pressure and moment

The wind received by a ship during its voyage is called relative wind, and the actual wind is called absolute wind. Therefore, the absolute wind is based on the Cartesian coordinates system (x_0Gy_0) and the relative wind is based on the ship's attached coordinate system (xGy). The ship's motion coordinate system under the influence of wind is shown in figure 2.

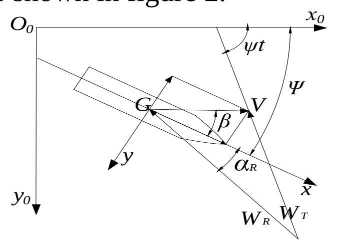

Fig. 2. Coordinate system of ship maneuvering motion under the influence of wind

The relative wind vector formula can be obtained from the figure 2.

$$\vec{W}_R = \vec{W}_T - \vec{V} \tag{4}$$

The relative wind speed can be written as:

$$W_R \cos\alpha_R = W_T \cos(\psi_T - \psi) - V\cos\beta,\quad W_R \sin\alpha_R = W_T \sin(\psi_T - \psi) + V\cos\beta \tag{5}$$

$$\alpha_R = \arctan\frac{w_{Ry}}{w_{Rx}} + \delta,\quad w_{Rx} = v_x + W_T\cos(\psi_T - \psi),\quad w_{Ry} = -v_y + W_T\sin(\psi_T - \psi) \tag{6}$$

Where W_T is the absolute wind speed, ψ_T is the absolute wind direction angle, indicating that the north wind is 0°, the east wind is 90°, and the value range is 0°~360°. V is the ship's velocity relative to water, W_R is relative wind speed, w_{Rx} and w_{Ry} are the components of W_R in the ship's additional coordinate system x and y, α_R is the relative wind direction angle, the wind is positive from the port side of the ship, negative from the star string, and the value range is-180°~180°, and is dimensionless, -sgn (w_{Ry}) when $Vx \geq 0$, and 0 when $Vx < 0$. δ is dimensionless, δ is $-\pi sgn(w_{Ry})$ when $v_x \geq 0$, and δ is 0 when $v_x < 0$.

Hydrodynamics are generated when wind acts on the hull and superstructure of the ship. The resultant force and the resultant torque are respectively F and N, and the expressions of X, Y and N are as follows:

$$X_w = 1/2\,\rho_a A_f W_R^2 C_{wx}(\alpha_R),\quad Y_w = 1/2\,\rho_a A_s W_R^2 C_{wy}(\alpha_R),\quad N_w = 1/2\,\rho_a A_f L_{oa} W_R^2 C_{wn}(\alpha_R) \tag{7}$$

Where the X_w and Y_w is the component of the F_w on the x and y axis respectively, ρ_a is air density, A_f is the orthographic projection area on the ship waterline, A_s is the side projection area above the ship waterline; L_{oa} is the total length of the ship, C_{wx}, C_{wy} and C_{wn} are wind pressure coefficient in the x and y axis direction on coordinate system (xGy) and wind pressure moment coefficient around the z axis. In this paper, the wind pressure coefficient and the wind pressure torque coefficient are calculated by the wind tunnel experiment obtained by Professor Tang Zhonggu[8].

2.3. Calculation of non-uniform wind pressure and torque

At present, the simulation of non-uniform wind is mainly realized by power spectral density method and white noise method. For better using of the actual measurement wind field data, we assume that the wind is a continuous medium and that the characteristic elements of the wind do not change within each second. To complete the real-time simulation of random wind the wind field data per second (equations (4)-(7) cycled in every second) was read based on Fortran language programming.

2.4. Hydrodynamic expression and Solutions of ship maneuvering motion equations

Based on the hydrodynamic model the expression of X, Y, and N can be written as:

$$\begin{aligned} X &= X_H(v_x, v_y, r) + X_R(v_x, v_y, r) + X_P(v_x, v_y, r) + X_W \\ Y &= Y_H(v_x, v_y, r) + Y_R(v_x, v_y, r) + Y_P(v_x, v_y, r) + Y_W \\ N &= N_H(v_x, v_y, r) + N_R(v_x, v_y, r) + N_P(v_x, v_y, r) + N_W \end{aligned} \tag{8}$$

For the stability and reliability of the calculation, the fourth-order Runge-Kutta method is used to solve the equation, and the discrete equations of ship position and parameters at any time are obtained, seeing reference [7] for details.

3. Mathematical model test of ship manipulation movement

According to the characteristics of the ship in the Three Gorges Reservoir area, the 5000 class t bulk carriers is selected as representative ship types. The navigation ability was tested through simulating the ship's direct navigation ability in still water, the turning ability in still water (25° rudder angle), the turning ability affected by wind in still water (15° rudder angle) (table 1). Results show that the ship's direct navigation ability is stable, the diameter of rotation D meet the requirements of 1.5~3.5 the length of the ship[9], and the trajectory of the ship moves downstream of the wind under the influence of wind is quite reasonable[10] (figure 3,4).

Tab. 1. Parameters of typical ship

Parameter	Overall length (m)	Moulded depth (m)	Designed draft (m)	Ship beam(m)	Design speed(km/h)	Standard displacement (t)	Lateral projection area (m^2)
Numerial number	106	7.5	3.3	17.5	18	5000	351
Parameter	Diameter of propeller (m)	Rudder height (m)	Area of rudder (m^2)	Rated power (kw)	Block coefficient	Prismatic coefficient	Frontal projected area (m^2)
Numerial number	4	3.5	11.1	2*735	0.587	0.631	110

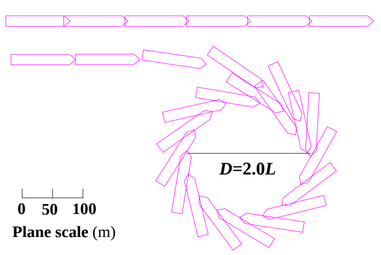

Fig. 3. The direct navigation and turning ability of typical ship

Fig. 4. Typical ship's turning track under the effect of wind

4. Model application and result analysis

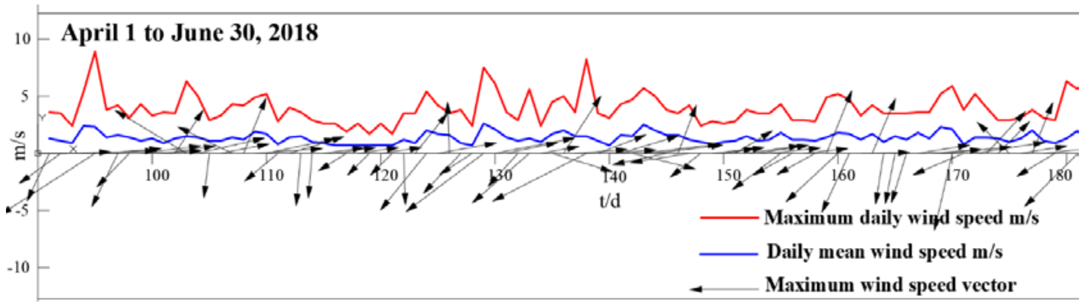

Fig. 5. Wind vector in the second quarter of Fengjie River in 2018

The Fengjie reach located in the perennial backwater area of the Three Gorges Reservoir. This section is located between Kuangu Xinwu section and Fengjie Yangtze River Bridge. The reach is straight with the length about 4.2km and it is relatively wide with the width about 600-800m. According to the measured data of the reach in 2010, the maximum flow velocity is about 1.01m/s with the 145m of the water level in Three Gorges Reservoir. Wind field data is adopted from the reach in 2018[11], and the second quarter with high wind speed change frequency is selected as the reference (figure 5).

4.1. *Numerical simulation scheme*

- The flow field data of the selected river reach are obtained by 2D numerical flow model, and then the navigation of the ship under the condition of still wind was simulated.
- Keeping the navigation rudder angle and other conditions of the ship under still wind remain unchanged, the simulation is carried out again by adding non-uniform wind.
- If the ship cannot fulfill its navigation due to wind influence after loading the wind field, then adjust the rudder angle of the ship and complete the navigation route.

4.2. *Numerical simulation results and analysis*

By analyzing the parameters of the ship's navigation, it can be known that when the wind field is loaded, the drift angle and heading angle of the ship increases obviously (table 2). From the navigation trajectory of the ship, it can be seen that the ship deviates from the channel due to the influence of wind effect after the non-uniform wind load. Navigation simulation cannot be completed due to unproper ship parameters (figure 6).

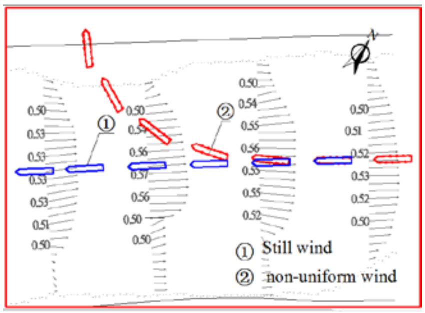

Fig. 6. Statistics of navigation parameters under the same rudder angle

Tab. 2. Navigation parameters of a ship at the same rudder Angle

Simulation conditions	Range (*m*)	Times (*s*)	Speed over bank (*m/s*)	Drift angle (°)	Heading angle (°)	Rudder angle (°)
Still wind	1323.5	305	4.62~4.85	0~2.1	235~281.2	-2~2
Non-uniform wind	1275	261	4.00~4.99	0~13.2	235~352.5	-2~2

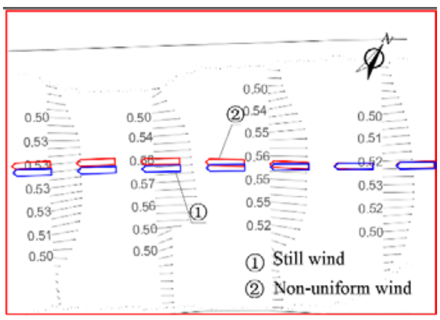

Fig. 7. Ship trajectories of different rudder angles with similar trajectory

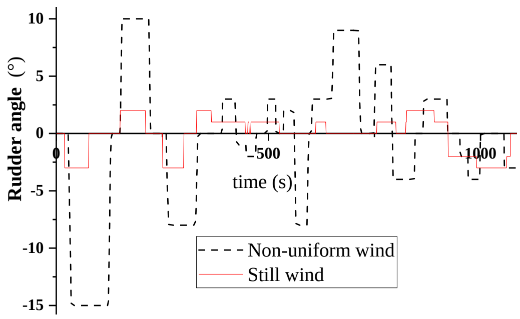

Fig. 8. ship maneuvering parameters of different rudder angles with similar trajectory

According to the change of water flow and wind field, the rudder angle of ship navigation is adjusted to make the ship fulfill navigation simulation (figure 7). Because the navigational trajectory is nearby, the parameters such as drift angle and heading angle hardly change. However, by analyzing the variation of rudder angle and steering frequency, it can be known that the steering frequency of the ship increases significantly after loading wind field (figure 8). Thus, in order to ensure the stability and safety of navigation, it is necessary to adjust the rudder angle and increase the steering frequency just in time.

5. Conclusions

In this paper, based on the depth integrated two-dimensional flow model and mathematical model of ship maneuvering motion under wind effect, the navigable trajectory of ship under non-uniform wind in selected reach is simulated. Navigation parameters of the ship show that the wind has a great influence on the ship's navigation and would make the ship's maneuvering complicated. Therefore, the ship needs to adjust the rudder angle in time according to the change of wind speed and direction (especially in the case of instantaneous gale) in order to ensure the navigation safety.

The simulation results show that the model can simulate the ship maneuvering motion and navigation status under wind effect quite well with convenience, efficiency and precision and expect to be more applicable.

Acknowledgments

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