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Modeling and time domain simulation of surf-riding for water-jet propelled ships

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Abstract: [**Objectives**] Surf-riding/broaching is one of the five stability failure modes included in the second generation intact stability criteria of the International Maritime Organization (IMO). The current regulation is limited in that it only applies to propeller-driven ships. To address this issue, this paper carries out some investigations into the surf-riding stability failures of water-jet propelled ships so that the regulation can be further completed. [**Methods**] On the basis of the mechanical model of the water-jet propulsion units and the one-dimensional surge motion equation of ships in following seas, a mathematical surf-riding motion model is built. The fourth-order Runge-Kutta method is used to solve the equation, and time domain motion simulation for the water-jet propelled ship is achieved. With a high-speed wave-piercing tumblehome ship as the sample ship, the characteristics of the conditions for the occurrence of surf-riding are obtained through systematic time domain numerical calculation. [**Results**] The numerical simulation results show that within the range of wave conditions required by IMO's second generation intact stability criteria, surf-riding occurs in 80.9% of conditions when the Froude number (Fr) is 0.4, and when the Fr is reduced to 0.3, the percentage drops to 59.4%. [**Conclusions**] This study provides a theoretical model and a numerical approach necessary to evaluating the surf-riding/broaching stability of water-jet propelled ships, and it can be used to evaluate the stability safety of this type of ship.

Key words: water-jet propulsion; surf-riding; motion model; second generation intact stability; wave-piercing tumblehome hull form; time domain simulation

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0 Introduction

Intact stability is one of the most important performance indexes for the safety design of ships. For this purpose, the International Maritime Organization (IMO) has formulated mandatory laws and regulations to ensure sufficient intact stability of ships. With the continuous emergence of new conceptual ship types, the development trend of large-scale ships is becoming more pronounced, and the applicability of the current criteria of ship intact stability to new ships has attracted increasing attention in the industry. Therefore, IMO began to formulate the new second-generation intact stability criteria for ships in 2009 (hereinafter referred to as the second-generation stability criteria). After ten years of repeated discussions, all the specifications were passed at the 6th (SDC6) meeting of the IMO Sub-Committee on Ship Design and Construction held in London, Britain in 2019 [1]. As a result, as the supplement and alternative solution for the current specifications, the second-generation stability criteria will change the former method of formulating criteria on experiences in the future. In addition, the

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criteria, by introducing the concept of direct assessment of stability, can provide personalized stability assessment methods for new conceptual ships and ships of super-dimension ratios. After the second-generation stability criteria are incorporated into the peremptory standard, a ship type needs to be improved if it cannot meet the requirements, and it can enter the international ship market only after meeting the requirements. Therefore, this is not only an important and urgent task faced by the design and research units of ships but also a huge challenge that must be faced by the development of the domestic shipbuilding industry [2].

Surf-riding/broaching is one of the five stability failure modes in the second-generation stability criteria. In following seas, the phenomenon that a high-speed ship suddenly loses its course-keeping ability and turns sharply at a high speed is called broaching. When the broaching occurs, the predetermined course still cannot be maintained under the maximum rudder angle, with violent yawing and large-angle heeling, which directly endangers the navigation performance and safety of the ship in the waves. Surf-riding is a prerequisite for broaching, and both navigation practices and ship model tests show that surf-riding is a dangerous state. Therefore, direct verification of surf-riding is required in the second-generation intact stability criteria by IMO.

According to the results of mechanical analysis, surf-riding is a dynamic equilibrium state of the longitudinal wave force, thrust, and resistance when the ship speed is equal to the wave speed. Up to now, the main methods used to predict the surf-riding include the analytical method [3-5], model test method [6], and numerical simulation method [7]. The current level 2 vulnerability criteria of surf-riding/broaching are checked through solving the critical propeller speed of the ship by the Melnikov method according to the bifurcation theory of nonlinear dynamics and thereby determining whether the ship is in danger of surf-riding.

Water-jet propulsion is a special type of ship propulsion. Compared with the traditional propeller-driven ships, water-jet propelled ships have excellent maneuverability and controllability and can operate in the condition of shallow draught. With the advantages of a small underwater acoustic signal, high propulsion efficiency at a fast ship speed, and great cavitation resistance, such ships have been widely used in the field of international shipbuilding industry (especially in the field of high-performance ships). However, water-jet propelled ships also face the risk of surf-riding. Given that the current specifications are only suitable for propeller-driven ships, in terms of verifying the second-generation intact stability criteria on water-jet propelled ships, some limitations still exist in the applicability of the criteria to ship types.

In response, a mathematical surf-riding model is built on the basis of a mechanical model of the water-jet propulsion units and a one-dimensional surge motion equation of ships in following seas. The fourth-order Runge-Kutta method is used to solve the motion model and achieve time domain motion simulation of water-jet propelled ships. With a high-speed wave-piercing tumblehome ship as the sample, the characteristics of the conditions for the occurrence of surf-riding are obtained through time domain numerical calculation. This study provides a theoretical model and a numerical approach to evaluating the surf-riding/broaching stability of water-jet propelled ships.

1 Surf-riding motion model of water-jet propelled ships

1.1 Mechanical model of water-jet propulsion

The thrust characteristics of the water-jet propulsion system are mainly described by the following two equations [8]. Eq. (1) is the thrust equation obtained according to the principle of conservation of momentum, and it describes the equilibrium relationship between the momentum change of the water flow after being accelerated by the pump and the produced thrust. Eq. (2) is the head equation derived in light of the energy conservation theorem, and it describes the equilibrium relationship that the sum of the kinetic energy, potential energy, and the flow losses of the water flow through the pump should be equal to the energy provided by the pump to the water flow.

$$T = \rho Q (V_{\mathrm{j}} - \alpha V_0) \tag{1}$$

$$H = \frac{(1+k_{\mathrm{j}})}{2g} \cdot V_{\mathrm{j}}^2 + (k_{\mathrm{i}} - \beta) \frac{V_0^2}{2g} + h_{\mathrm{c}} \tag{2}$$

where T is the thrust produced by the water-jet propulsion system; Q is the flux; ρ is the density of the aqueous medium; V_{j} and V_0 are the jet velocity and average inflow velocity respectively; α is the influence coefficient of the boundary-layer of the hull on the inflow momentum; H is the head of the pump; g

is the acceleration of gravity; h_c is the height from nozzle center to the still water surface; k_j and k_i are the coefficients of flow losses at the nozzle and in the inflow channel respectively; β is the utilization factor of stamping that reflects the impact of the boundary-layer of the hull on the inflow kinetic energy and is generally expressed as [9]:

$$\beta \approx \alpha^2 \tag{3}$$

When predicting the propulsion performance of a water-jet propulsion system, we assume that ρ, g, h_c are known quantities, and k_j, k_i represent the coefficients of momentum and energy losses. If accurate data are unavailable, the empirical values can generally be selected [8], such as k_j = 0.02 – 0.03, k_i = 0.2–0.3, and α = 0.85–0.9.

1.2 Surf-riding motion model of the water-jet propelled ships

The mathematical model of the surf-riding of a ship in the regular wave involves the three coordinate systems shown in Fig. 1. The inertial coordinate system O_E-X_EZ_E is consolidated with the ground, and the ship travels along the direction of wave propagation in the system at the ship speed of V_s. In the wave coordinate system O-$\xi\zeta$, the longitudinal position of the origin of coordinates O corresponds to the trough and moves in the inertial coordinate system at the wave speed of c_w. The motion coordinate system G-xz is consolidated with the hull, and the longitudinal position of the origin of coordinates G corresponds to the barycenter of the ship. The longitudinal distance between G and O represents the relative position of the ship to the wave. In the figure, ξ_G/λ is the position of the ship relative to the waves, where λ is the wavelength.

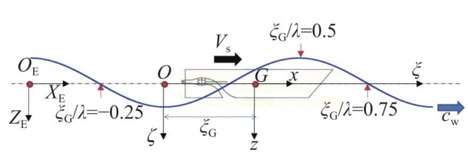


Fig. 1 Coordinate systems of the surf-riding motion model

On the basis of the motion equation of single-degree-of-freedom surge of a ship in the following sea, the mathematical equation of surf-riding builds the equilibrium relationship of the resistance, wave force, and inertia force acting on the ship and the thrust generated by the water-jet propulsion system, as shown in Eq. (4).

$$(m+m_x)\ddot{u}+[R(u)-(1-t_P)\cdot T(n,u)]-f_W=0 \tag{4}$$

where m is the mass of the ship; m_x is the added mass of surge; u is the real-time surge speed of the ship in the inertial coordinate system; $\ddot{u}$ is the acceleration of surge; R is the resistance acting on the ship; T is the function of the speed of the pump n and u; t_P is the thrust-deduction factor; f_W is the wave surge force acting on the ship.

With the transformation relation between the inertial coordinate system and the wave coordinate system, the following mathematical equation of surf-riding in the wave coordinate system can be deduced:

$$(m+m_x)\ddot{\xi}_G+[R(\dot{\xi}_G+c_W)-(1-t_P)\cdot T(n,\dot{\xi}_G+c_W)]-f_W(\xi_G)=0 \tag{5}$$

where ξ_G is the relative longitudinal position of the ship to the origin of the coordinates in the wave coordinate system and the dots above indicate the derivative to time.

Because the difficulty in modeling the surf-riding of water-jet propelled ships is that the ship speed changes at any time under the action of the wave force, which affects the inflow speed of the pump and changes the thrust generated by the water-jet propulsion system. Therefore, the key to the modeling is to correctly predict the real-time thrust generated by the water-jet propulsion system at a variable ship speed. In terms of surf-riding modeling, the difference between water-jet propelled ships and propeller-driven ships is also mainly reflected in the propulsion model, and other components such as resistance and wave force can be modeled according to the relevant requirements in the second-generation stability standard of IMO.

The ship resistance is simulated by the polynomial fitting:

$$R(u)=\sum_{i=1}^{N_R} r_i u^i \tag{6}$$

where N_R is the fitting order, and the third-order or fifth-order polynomial fitting is suggested by IMO, and r_i is the coefficients after fitting.

The thrust model of the water-jet propulsion system is the focus of this study. The equilibrium relationship of the head needs to be established to predict the real-time thrust of the water-jet propulsion system at a variable ship speed. Eq. (2) shows the head required for the water-jet propulsion system to generate a certain amount of thrust, and whether the pump can reach this head is determined by the hydraulic characteristics of the pump itself. According to Reference [10], the head provided by the pump can be approximated by the following equation based on the experimental data of the pump model:

$$H(n) = \left(\frac{n}{n_0}\right)^2 \cdot \left[\left(\frac{n_0}{n}\right)^2 q_2 \cdot Q^2 + \left(\frac{n_0}{n}\right) q_1 \cdot Q + q_0\right] \quad (7)$$

$$Q = V_j A_j \quad (8)$$

where n_0 is the rated speed of the pump; q_0, q_1, q_2 are the fitting coefficients of the head-flux (H-Q) testing curve corresponding to n_0; A_j is the area of the nozzle.

The model in this paper considers that the average inflow velocity V_0 of the pump is equal to the real-time surge velocity u. When the speed of the pump n remains constant, the actual flux of the pump at the current moment can be obtained by solving simultaneous equations of Eq. (2) and Eq. (7). Eq. (1) can then be used to calculate the thrust generated by the water-jet propulsion system at this time.

The wave surge force f_W is also modeled according to the requirements of the IMO standard, and the details are as follows:

$$f_W(\xi_G) = -f \sin(k\xi_G) \quad (9)$$

$$f = \rho g k \zeta_a \sqrt{F_c^2 + F_s^2} \quad (10)$$

$$F_c = \sum_{i=1}^{N} S(x_i) \exp[-0.5kd(x_i)] \sin(kx_i) \Delta x_i \quad (11)$$

$$F_s = \sum_{i=1}^{N} S(x_i) \exp[-0.5kd(x_i)] \cos(kx_i) \Delta x_i \quad (12)$$

where k is the wavenumber; ζ_a is the amplitude of the regular wave; x_i is the vertical coordinate of the ship section of different stations in the inertial coordinate system; $d(x_i)$ is the draft of each section in still water; $S(x_i)$ is the submerged area of each section in still water; N is the number of stations; f is the amplitude; F_s and F_c is the sinusoidal component and cosine component of the force, respectively.

2 Time domain surf-riding simulation for water-jet propelled ships

The fourth-order Runge-Kutta method is used to solve the ordinary differential equation corresponding to Eq. (5) and thereby obtain the time history of the ship speed relative to the wave speed. If the speed eventually approaches zero (the ship speed is equal to the wave speed), it means surf-riding happens. Otherwise, the ship takes on periodic motion under the action of the wave. In the following sections, a high-speed wave-piercing tumblehome hull is taken as an example to study the characteristics of the conditions for surf-riding of this type of ship by time domain numerical calculation.

2.1 Particulars of sample ship

The sample ship is a water-jet propelled high-speed wave-piercing tumblehome ship as shown in Fig. 2, and its main particulars are shown in Table 1. The ship is equipped with four mixed-flow water-jet propulsion units, and the Froude number corresponding to the design ship speed is Fr=0.4. The mass of the sample ship is m = 2 834 t, and the added mass of the surge is set to be m_x = 0.1 m according to the IMO standard. The thrust-deduction factor is set to be t_P = 0.02 according to the results of the model test. The resistance data of the sample ship are obtained on the basis of model tests and fitted by the cubic polynomial.

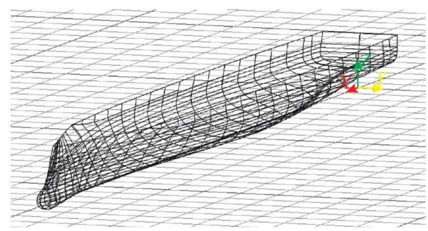


Fig. 2 Wave-piercing tumblehome hull lines of the sample ship

Table 1 Main particulars of target ship

Particluars	Numerical value
Ship length L/m	110.0
Molded breadth B/m	13.4
Draft d/m	3.9
Block coefficient C_B	0.481
The longitudinal position of buoyant center (The midship front is positive) L_{CB}/m	−2.5
The vertical height of barycenter (The up baseline is positive) V_{CG}/m	5.8
The diameter of nozzle D_j/m	0.75
The rated speed of pump n_o/(r·min^{-1})	603.6
The height from nozzle center to still water surface h_c/m	0.3

The hydraulic performance particulars of the pump are obtained from the bench test and converted to those of an actual pump as shown in Fig. 3. In the figure, the dots correspond to the test results of the pump at the rated speed, and the solid line presents the quadratic polynomial fitting of the test points. The coefficients corresponding to the pump are as follows: k_j = 0.020 3, k_i = 0.24, and α = 0.88.

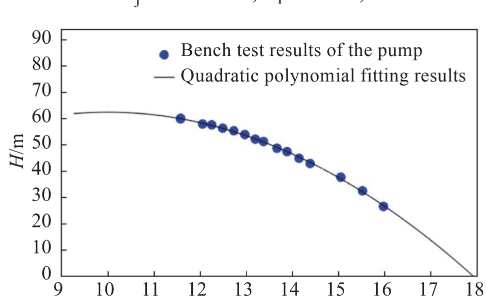


Fig. 3 Experimental results of pump's hydraulic performance

2.2 Time domain simulation calculation results

Numerical simulation calculation is performed in the condition of the typical regular wave at the design ship speed (Fr = 0.4). In the regular wave of the following sea with the ratio of the wave length to the ship length λ/L = 1.5 and the wave steepness H/λ = 0.05, the simulation results of the sample ship's position ξ_G/λ and speed relative to the wave are shown in Fig. 4. As can be noted from this figure, the ship's position relative to the wave reaches a stable value after a few cycles of short oscillations, and the speed relative to the wave also approaches zero, which indicates that surf-riding happens to the sample ship in this condition.

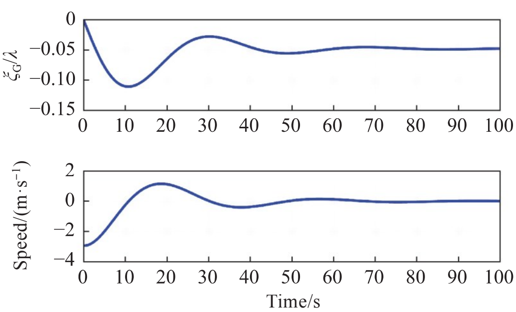


Fig. 4 Simulation results of the sample ship's position and speed relative to wave (Fr = 0.4, λ/L = 1.5, H/λ = 0.05)

Fig. 5 shows the time history curves of the forces acting on the sample ship in the above typical regular wave conditions. According to further analysis, the ship speed is lower than the wave speed in the initial state, but the ship is accelerated by the wave force. The hydrostatic resistance is higher at this time. At the same time, the velocity of the pump inflow is accelerated while the pump thrust is reduced. The ship reaches an equilibrium state after about 60 s under the combined action of the wave force, resistance, and thrust.

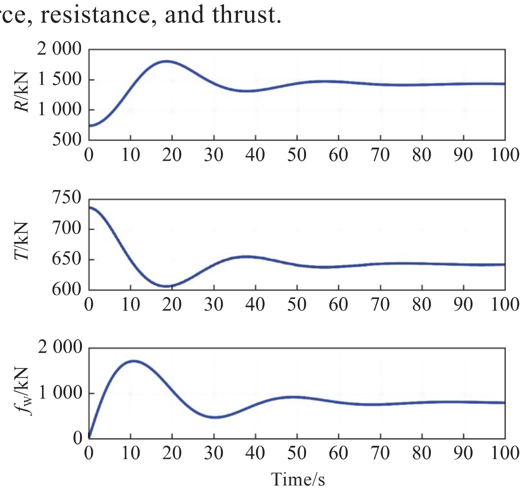


Fig. 5 Simulation results of forces acting on sample ship (Fr = 0.4, λ/L = 1.5, H/λ = 0.05)

For comparison, the simulation results after increasing λ/L to 2.5 are shown in Fig. 6 and Fig. 7. Because the wave speed is significantly higher than the ship speed at this time, the ship cannot achieve the equilibrium state in surf-riding. Therefore, the ship constantly retrogresses relative to the wave in terms of position, whereas the speed and force relative to the wave take on periodic oscillation.

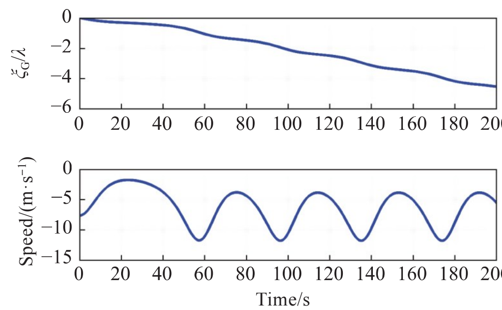


Fig. 6 Simulation results of the sample ship's position and speed relative to wave (Fr = 0.4, λ/L = 2.5, H/λ = 0.05)

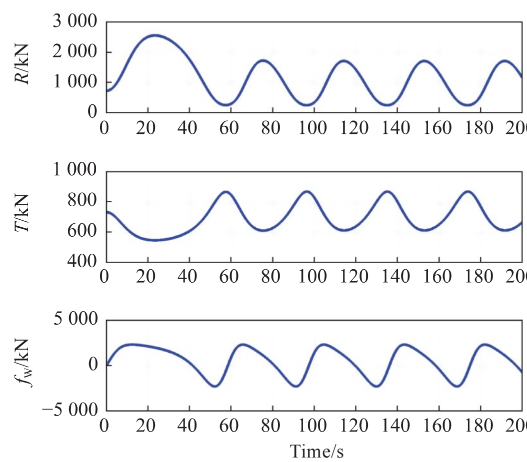
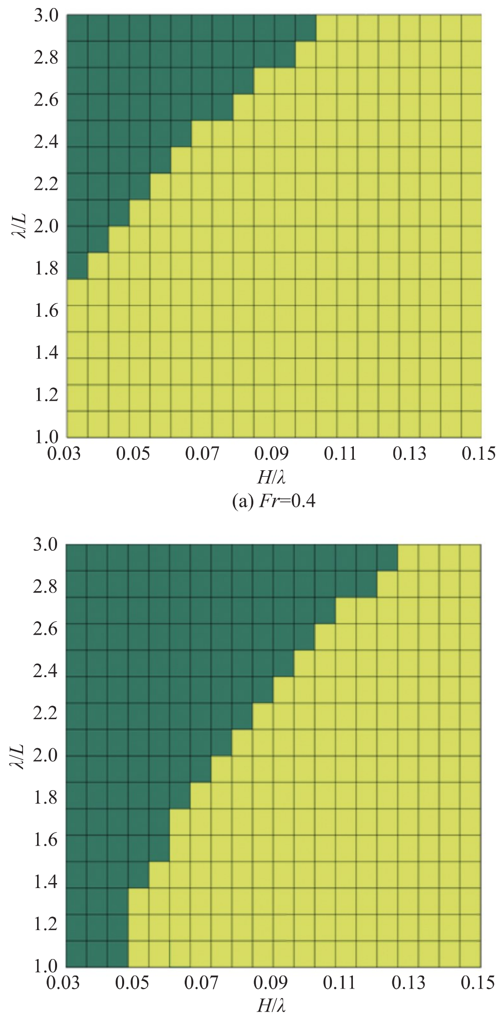


Fig. 7 Simulation results of forces acting on the sample ship (Fr = 0.4, λ/L = 2.5, H/λ = 0.05)

This paper uses the proposed surf-riding motion model and time domain simulation method to calculate and study the ranges of λ/L and H/λ required by the IMO's level 2 vulnerability criteria check of surf-riding/broaching respectively. The surf-riding occurrence conditions at Fr = 0.4 (n = 513.4 r/min) and Fr = 0.3 (n = 349.3 r/min) are shown in Fig. 8. In the figure, the dark color corresponds to the area without surf-riding occurrence and the light color represents the area with surf-riding occurrence. According to the range of wave steepness (H/λ = 0.03–0.15) on the horizontal axis and the range of the ratio of the wave length to the ship length (λ/L = 1.0–3.0) on the vertical axis shown in Fig. 8, a total of 320 conditions are simulated and calculated. The selected range of conditions is in accordance with the requirement of the level 2 vulnerability criteria check in IMO's second-generation surf-riding/

broaching stability criteria. In this range of conditions, the ship is more likely to broach after the surf-riding.



(a) Fr=0.4

(b) Fr=0.3

Fig. 8 Simulation results of the surf-riding occurrence conditions

The calculation results show that the proportion of the surf-riding occurrence conditions is as high as 80.9% when Fr=0.4 and decreases to 59.4% when Fr=0.3. According to the distribution of the surf-riding occurrence areas, when λ/L is close to 1, surf-riding occurs even at a small wave steepness H/λ. With the increase in λ/L, the minimum wave steepness H/λ required for surf-riding occurrence also increases. Therefore, the sample ship is more prone to surf-riding occurrence when the wave length is similar to the ship length, and lowering the ship speed can effectively reduce the proportion of surf-riding occurrence conditions. The simulation and calculation results show that the final equilibrium position of the ship after surf-riding is mostly on the downslope side of the wave, where there is a strong likelihood of more broaching.

3 Conclusions

Given that the current second-generation stability criteria of the IMO only apply to propeller-driven ships, a mathematical model of surf-riding is built in this paper for water-jet propelled ships according to the mechanical model of the water-jet propulsion units and a one-dimensional surge motion equation of ships in following seas, and it is expected to provide a theoretical model and a numerical analysis method for the surf-riding/ broaching stability assessment of water-jet propelled ships and facilitate the stability safety assessment of this type of ship. With a high-speed wave-piercing tumblehome ship as an example, the characteristics of conditions for the surf-riding of this type of ship are obtained by systematically implementing time domain numerical calculation. The results show that the sample ship is more prone to surf-riding when the wave length is close to the ship length, and the risk of surf-riding can be effectively reduced by lowering the ship speed.

On the basis o f this study, multi-degree-of-freedom motion models of water-jet propelled ships can be developed in the future. However, for the simulation of the broaching motion, a steering motion model with at least four degrees of freedom needs to be built for motion modes of surge, swaying, yawing-swing, and rolling. Meanwhile, the forces on water-jet propelled ships in the wave should also be modeled.

References

[1] IMO. Finalization of second generation intact stability criteria-report of the working group: part 1-WP. 5/Annex 4 [C]//Ship Design and Construction(SDC) 3rd Session. London, UK: IMO, 2016: 1−34.

[2] GU M, LU J, WANG Z R. Overview on the progress of the second generation intact stability criteria in IMO [J]. Shipbuilding of China, 2014, 55(4): 185−193 (in Chinese).

[3] MAKI A, UMEDA N. Numerical prediction of the surfriding threshold of a ship in stern quartering waves in the light of bifurcation theory [J]. Journal of Marine Science and Technology, 2009, 14(1): 80−88.

[4] MAKI A, UMEDA N, RENILSON M, et al. Analytical formulae for predicting the surf-riding threshold for a ship in following seas [J]. Journal of Marine Science and Technology, 2010, 15(3): 218−229.

[5] WU W, SPYROU K J, MCCUE L S. Improved prediction of the threshold of surf-riding of a ship in steep following seas [J]. Ocean Engineering, 2010, 37(13): 1103−1110.

[6] UMEDA N, HAMAMOTO M. Capsize of ship models in following/quartering waves: physical experiments and nonlinear dynamics [J]. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 2000, 358(1771): 1883−1904.

[7] WANG T H, MA N, GU X C, et al. Effect of propeller thrust reduction on ship surf-riding/broaching prediction [C]//Proceedings of the 13th International Workshop on Stability of Ships and Ocean Vehicles. Kobe, Japan: [s. n.], 2018.

[8] DING J M, WANG Y S. Two methods for expressing the propulsive performance curves of marine waterjets [J]. Journal of Harbin Engineering University, 2010, 31 (1): 20−25 (in Chinese).

[9] WANG L X, CAI Y L. Design theory and technology of waterjet propulsion and propulsion pump[M]. Shanghai: Shanghai Jiao Tong University Press, 2018 (in Chinese).

[10] KONG Q F, WU J M, YU G F, et al. Dynamic simulation of the turning transient process of waterjet propulsion warship [J]. Computer Simulation, 2006, 23(8): 12−16 (in Chinese).

喷水推进船骑浪运动建模及时域仿真

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摘　要:[**目的**]船舶骑浪/横甩是国际海事组织(IMO)新纳入船舶第二代完整稳性衡准中的 5 种稳性失效模式之一。针对当前规范仅适用于螺旋桨推进船的局限性,研究喷水推进船骑浪失稳的问题,为后续进一步完善规范奠定基础。[**方法**]基于喷水推进装置的力学模型和船舶在随浪中的一维纵荡运动方程,建立船舶骑浪运动的数学模型,利用四阶 Runge-Kutta 法求解模型,实现船舶时域运动仿真。以一艘高速穿浪内倾船型为例,系统性开展时域数值计算,以得出此类型船舶发生骑浪现象时的工况特点。[**结果**] 通过数值仿真,得出了目标船舶在第二代完整稳性衡准要求的波浪工况范围内的预报结果:Fr=0.4 时,有 80.9% 的工况发生骑浪;Fr=0.3 时,骑浪发生比例降至 59.4%。[**结论**]研究成果既可为喷水推进船的骑浪/横甩稳性评估提供理论模型和数值分析的手段,也可用于对此类型船舶进行稳性安全评估。

关键词:喷水推进;骑浪;运动模型;第二代完整稳性;穿浪内倾船型;时域仿真