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The Car-Following Model of Safe Navigation of Polar Route

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ABSTRACT. *This paper starts from the "Ice Silk Road"--the characteristics of the ship on the Arctic route, combined with the special environment of the channel, using the traffic flow theory and the following theory to establish a car-following distance model suitable for the Arctic route. The state of navigation of the ship is analyzed; from the macroscopic calculation of the pitch of the heel, the ship's heeling distance and the speed of the icebreaker are obtained, thus improving the navigation safety of the Arctic route.*

KEYWORDS: *car-following model, polar route*

1. Introduction

In an Arctic climate impact assessment report, the Arctic has experienced rapid changes in the ecological, social and economic aspects in the past 10 years. Later, at the Arctic Development and Maritime Conference in 2007, two routes on the Arctic Ocean were discussed: the Northwest Passage and the Northeast Passage. Most of the Northwest Passage is located on the northern coast of Canada, from the Bering Strait eastward through the Canadian Arctic Archipelago to the Davis Strait, connecting the Atlantic Ocean and the Pacific Ocean; the Northeast Passage is located in the north of Russia, from the Nordic region to the east through the five seas until the Bering The strait connects East Asia and Northern Europe. Although only ships with icebreakers can sail at certain times during the summer, according to the speed of melting ice, the Arctic channel will be opened in 2030, and there will be no more freezing in the Arctic Ocean in 2050.

The opening of the Arctic route will greatly shorten the sea distance between East Asia and North America and Europe, and become the most convenient transportation route at sea. The voyage is 15%-50% shorter than the traditional route. It can be seen that the opportunities and challenges brought by the Arctic routes are unprecedented in the shipping industry. At present, maritime transportation has completed 80% of the trade, and the opening of the Arctic route is not only the addition of a route route, which shares the volume of traditional routes, reduces the

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weight and status of traditional routes, and thus affects the world shipping pattern. The country’s trade has brought about development opportunities.

On August 27, 2013, following the “Snow Dragon”, China’s COSCO Group’s “Yongsheng” started from Taicang, Jiangsu, to Rotterdam, the Netherlands, and became the first Chinese merchant ship to reach Europe through the Northeast Passage. Which is an epoch-making meaning. In 2016, 4 vessels of COSCO Shipping successfully passed through the Northeast Passage. On September 6, 2017, China's eighth Arctic scientific expedition team entered the Beaufort Sea on the "Snow Dragon" and successfully traversed the Central Channel for the first time. The navigation distance and navigation time were greatly shortened, further promoting the ship's flight to the Arctic. Commercial use. "Ice Silk Road" - the Arctic route is in a bad environment. In the heavy ice area, an icebreaker is needed to assist in icebreaking. The sailing ship often sails in the form of a fleet, following the icebreaker, in its ice-free trail. Otherwise, the passage will soon be blocked by broken ice and the ship will lose its safe passage in the ice. In addition, the ship will be affected by drifting ice and dense fog, and it is necessary to fully grasp the distance from the icebreaker or the fore boat in the special environment of the Arctic route. The car-following model is mainly used in vehicle traffic flow, and it is rarely used in the ship field and needs to be applied under certain conditions. The so-called specific conditions mean that the ship is lined up on a one-way channel that cannot exceed the ship, and the rear ship follows the preceding ship. Domestic research on ship-following theory focuses on inland ships

2. Research status at home and abroad

From 1950, Reuschel used the dynamics theory to analyze the traffic flow in the vehicle queue, and gradually formed the concept of vehicle following. [1]The GM (General Motors, abbreviated as GM) model was proposed and established by General Motors in the middle of the last century. [2] It is a very influential basic research work of General Motors in the theory of car-following. [3] Based on the stimulus-response theory, Chandler used the experimental data of the GM test track to establish a linear car-following model to describe the relationship between the acceleration of the rear vehicle and the difference between the front and rear vehicles. [4] In 1991, Gazis proposed the expression of the GM model, so it is also called the Gazis-Herman-Rothery model, referred to as the GHR model. [5] It is based on the linear car-following model and becomes a vehicle based on the stimulus-response principle. [6] The most classic model of the following behavior. It overcomes the limitation of the linear car-following model considering only the influence of the difference between the front and rear speeds on the acceleration change of the following car. [7] On the original basis, the car spacing and the speed of the car are considered. It can reflect the influence of the speed of the car, the distance between the front and the rear and its relative speed on the acceleration of the car, but this model is more suitable for the frequent deceleration of the car, and is not suitable for the general car-following state. [8] In 1995, Bando proposed the Optimal Velocity (OV) model from the perspective of statistical physics. Through

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the optimization of the speed of the car, the stability of traffic flow was realized. It described the phenomenon of stop-and-go during traffic flow. [9] In 1998, Helbing proposed the Generalized Force (GF) model, which considered the effect of speed difference on the acceleration of the car, and proposed the concept of negative speed difference. [10] The difference between the speed of the vehicle and the speed of the leading vehicle, and the negative speed difference as the dependent variable, constructs the Heaviside function about the negative speed difference. [10] In 2001, JIANG established and proposed a Full Velocity Difference (FVD) model. On the basis of considering the influence of negative speed difference, the model also considers the influence of positive speed difference on the acceleration of the following car, that is, considering that the speed of the lead car is smaller than that of the car, and the speed of the lead car is greater than that of the car. A more comprehensive description of the car-following phenomenon of traffic flow. [11]

3. Calculation of car-following model

3.1 Introduction to car-following model

This paper draws on the safety distance-based car-following theory proposed by Gipps in 1981. [12]

$$v_n(t+\tau) = min\begin{cases} v_n(t) + 2.5a_n\tau\left(1-\frac{v_n(t)}{v_n}\right)\sqrt{0.025+\frac{v_n(t)}{v_n}} \\ -b_n\left(\frac{\tau}{2}+\theta\right)+b_n\left\{2[x_n(t)-x_n(t)-S_{n-1}]-\tau v_n(t)+\frac{v_{n-1}^2(t)}{b_{n-1}}\right\} \end{cases}$$

a_n is the maximum acceleration of vehicle n; v_n is the upper speed limit of vehicle n in the current traffic environment; b_n is the maximum deceleration of vehicle n; τ is the reaction time of the rear vehicle driver; θ is the additional reaction time for safety; X_n is the position of vehicle n; S_{n-1} is the length of vehicle n -1.

The Gipps car-following model analyzes the free-running state and the speed of the vehicle in a crowded state, and calculates the minimum safe distance of the car following. This paper draws on the Gipps car-following model to establish a car-following model for the Arctic route.

Sailing in the Arctic route requires icebreaker assistance when the ice conditions are severe. The ship follows the form of a single ship or fleet. The icebreaker's ice-breaking work is not stable. Therefore, it is necessary to maintain a certain safe distance (including the distance from the icebreaker and the distance between the ships in the fleet). This safety distance is the safety clearance of the ship. The distance between the ship and the preceding ship after braking is greater than the safety margin of the ship that the driver is generally unwilling to invade. The basic following mode of the ship is shown in Figure 1.

As shown in Figure 1, the initial position of the n-1th ship is X_{n-1}, and the initial position of the nth ship is X_n. When the ship n-1 starts braking, it is the time of

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inspection. When the front ship brake is completed. The distance between the front ship position X_{stop} n-1 and the initial position X_n of the rear ship n is S_1.

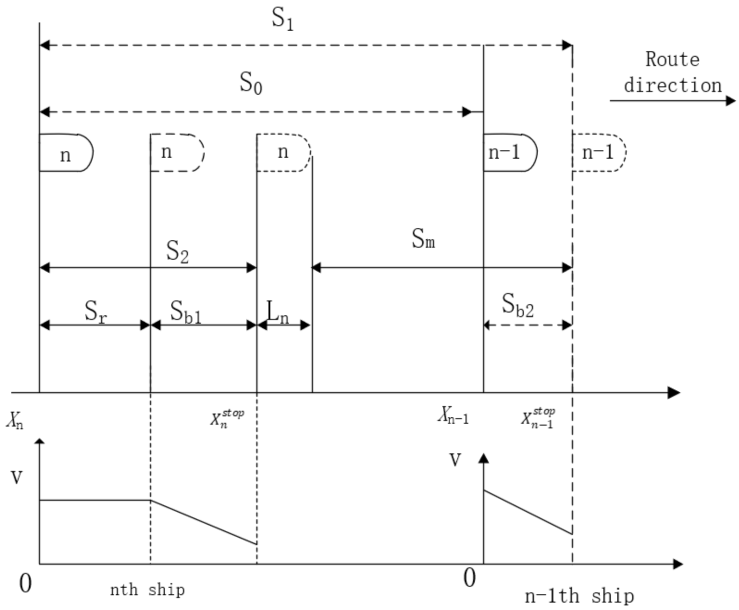

Figure. 1 the basic model of the following behaviour of the ship

$$S_1 = S_0 + S_{b2}$$

S_0 is the distance between the two ships before the front ship n-1 brake; S_{b2} is the braking distance of the front ship n-1. The driver of the rear ship n is from the operating condition of the previous n-1 and the command to the host to start braking is tr (including the driver's reaction time τ (0. 5 s ~ 1.5 s) and its operating time (0.7 s ~ 1.0 s), and the time from the command to the actual braking of the host θ (4 s ~ 6 s), the average available t_r is 7 s, then the boat n travels during this time Distance, the reaction distance is as follows:

$$S_r = vt_r$$

then the distance from the ship to the front ship situation and the reaction to the final stop is as follows:

$$S_2 = S_r + S_{b1}$$

After the two ships have completed the braking, they must maintain a safe distance S_m, so the separation distance after the two ships are completely stopped should be greater than the safety margin S_m, that is, $S_1 - S_2 - L_n \geq S_m$, available:

$$S_0 + S_{b2} - (S_r + S_{b1}) - L_n \geq S_m$$

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Expressed as:

$$S_0 \geq S_m + S_r + L_n + k_b S_{b1}$$

$$k_b = 1 - \frac{S_{b2}}{S_{b1}}$$

K_b is the brake operating coefficient; Sm can take 1/4 times the length of the ship, which is $0.25L_n$. When the current ship speed is reduced less than the speed of the rear ship, the two ships will never collide and will not be considered. When the current rear braking distance is equal, (Sb1=Sb2), the braking operation coefficient k_b is 0. At this time, S_0 is the minimum safe distance, that is,

$$S_{min} = S_m + S_r$$

If the fore boat (such as an icebreaker) suddenly stops moving when encountering the ice floe, at this time, the front ship braking distance S_{b2} is 0, and the braking operating coefficient k_b is 1, the maximum absolute safety distance S_{max} is as follows:

$$S_{max} = S_m + S_r + S_{b1}$$

In the actual voyage of the Arctic route, it is difficult to accurately estimate the braking behavior of the preceding ship, and often rely on the driver's navigation experience to control the heel distance. Especially in the case of an icebreaker pilot, it is necessary to maintain a high concentration of attention. At the same time, foggy weather in the Arctic route is also very common. Drivers often reduce the speed or maintain a large safety margin for safety reasons, which will have a great impact on the driver's mentality. Therefore, the introduction of the parameter β reflects the psychological impact of both on the driver. Therefore, the actual safety spacing S_a is as follows:

$$S_a = S_m + S_r + k_b S_{b1} \beta$$

3.2 Bow spacing

The ship's radar antennas are all at the stern, and the captains here are all valid captains, so the actual safety margin should be added to the ship length L_n of the ship n.

$$S_d = S_m + L_n$$

In the field of transportation, the speed of the ship is often used to express the speed of the ship. The conversion relationship between the speed and the speed is as follows:

$$V=0.51u$$

Bringing the formulas (11) and (12) into the formula (10), the actual ship spacing d is as follows:

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$$d = S_m + L_n + 0.51ut_r + k_b S_{b1}\beta$$

$$d_{min} = S_m + L_n + 0.51ut_r$$

$$d_{max} = S_m + L_n + 0.51ut_r + S_{b1}$$

$$d_{min} \leq d \leq d_{max}$$

Distance between bows (m) when d_{min} is S_{min}; Head spacing (m) when d_{max} is S_{max}.

3.3 Ship speed

In the Arctic route, in order to prevent the icebreaker from suddenly hitting the wall, it is often necessary to maintain the maximum head spacing d_{max}. In fact, in the course of ship navigation, if the speed of the preceding ship is faster than that of the ship, the rear ship tends to maintain a car-following distance slightly smaller than the safe distance. When the forward speed of the ship is less than that of the rear ship, the rear ship tends to maintain a car-following distance slightly larger than the safe distance. In summary, the following spacing should be a function of the safety distance and relative speed. It is known from the foregoing that in order to ensure that the two ships do not collide, they must meet

$$X_{n-1}^{stop} - X_n^{stop} \geq S_d$$

$$X_{n-1}^{stop} = X_{n-1} + \frac{(0.51u_{n-1})^2}{2a_{n-1}}$$

$$X_n^{stop} = X_n + 0.51u_n t_r + \frac{(0.51u_n)^2 - (0.51u_a)^2}{2a_{n-1}}$$

$$X_{n-1} + \frac{(0.51u_{n-1})^2}{2a_{n-1}} - \frac{X_n + 0.51u_n t_r + (0.51u_n)^2 - (0.51u_n)^2}{2a_n} \geq S_d$$

Then

$$u_n \leq -a_n t_r + \sqrt{a_n^2 t_r^2 + 2a_n(X_{n-1} - X_n - S_d) + \frac{(0.51u_0)^2}{a_n} + \frac{(0.51u_{n-1})^2}{a_{n-1}}}$$

4. Model parameter verification and application

Affected by the Arctic Ocean sea ice factor, ships capable of passing the Arctic route are limited. For example, in the Russian Rules for Navigation of the North Sea

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Channel, when there is moderate ice in the Chukchi Sea, the Eastern Siberian Sea and the Laptev Sea, ships that are not strengthened by the ice-free zone not allowed to pass. This paper mainly takes the "Millennium" wheel that has driven through the northeast channel of the Arctic route as an example to analyze the driving performance. The Arctic region can generally be divided into three types: open sea, ice floes and continental margin ice. Different icebreaking methods should be adopted under different sea conditions. Traditional icebreakers use icebreaking and icebreaking. Continuous icebreaking is suitable for sea areas with small ice strength and thin thickness. If the ice layer is thicker and exceeds the maximum icebreaking thickness of the icebreaker design, or in the more complex ice, thick ice and more severe iceberg, use the collision ice method to open the bow to Ice surface, crushing the ice with its own gravity and ballast water. The ice thickness of the Arctic route generally does not exceed the maximum icebreaking thickness of the icebreaker design. Therefore, this paper only considers the continuous icebreaking method. In order to maximize the safety of the ship, in the case of an emergency, the icebreaker suddenly “crash-type” the ship, for example, calculate the distance between the “Millennium” and the icebreaker and the minimum safety distance, and compare with the actual situation.

4.1 Sailing resistance of the "tianxi" ship

The "tianxi" wheel has a rated power of 8000 kW and a design speed of 16 kn. The speed of the heel after the icebreaker is generally around 10 kn, the ship's draught is 8.8 m, the ship's displacement is 25,112 t, the ship's length is 165 m, and the ship's width is 25.0 m. The shroud propeller ship has a water velocity of 5.42 m/s. According to the calculation formula of the ship's navigational resistance, combined with the specific ship data of the "Yongsheng" wheel, the ship's navigational resistance is calculated. The navigational resistance of the "Yongsheng" wheel in the road of the icebreaker is affected by many factors, mainly weather factors and seawater factors. This paper mainly considers the seawater factor. The seawater factor determines the ship's navigational resistance in the water—water flow resistance, wave resistance, and ice breaking resistance.

4.2 Water flow resistance

In terms of ship navigation resistance calculation, Zwankov method is relatively simple to use, and this method is adopted by China's waterway community. The Zwankov method mainly includes the water flow resistance R_v and the water surface ratio reduction resistance R_J received by the ship, while the navigation resistance of the sea ship is mainly the water flow resistance and the wave resistance. Therefore, the Zwankov method is used to solve the water flow resistance.

$$\mathrm{Fr} = \frac{v}{\sqrt{gl}} = \frac{5.42}{\sqrt{9.8 \times 160}} \approx 0.14$$

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$$A_0 = \beta BT = 0.93 \times 25 \times 8.8 = 204.6m^2$$

$$\delta = \frac{W}{LBT} = \frac{25112}{165 \times 25 \times 8.8} \approx 0.7$$

$$S = L_w(1.8T + \delta B) = 165 \times (1.8 \times 8.8 + 0.7 \times 25) = 5501.1m^2$$

$$\xi = \frac{17.7 m_0 \delta^{2.5}}{(\frac{L}{6B})^3 + 2} = \frac{1.77 \times 0.7^{2.5}}{(\frac{165}{6 \times 25})^3 + 2} = 0.22$$

$$R_v = fsv^{1.83} + \xi \delta A_0 v^{1.7+4Fr}$$

$$= 0.17 \times 5501.1 \times 5.42^{1.83} + 0.22 \times 0.7 \times 204.6 \times 5.42^{1.7+4\times0.14}$$

$$= 22048.22kg = 216072.6N$$

R_v is the water flow resistance; f is the friction coefficient of the motor boat, which is taken as 0.17 ;S is the ship's water immersion area; T is the ship's draft; δ=0.58~0.60; W is the ship's displacement; L is the ship's length; L_w is the ship's waterline length, which is approximately equal to the length of the ship; B is the ship's width; ξ is the residual resistance Coefficient; v is the relative speed of the ship and water; the coefficient of the propeller ship is m_0 = 1.0, m_0 = 1.2 for the shroud; A_0 is the ship's cross-sectional area; the ship's cross-section coefficient β = 0.93; F_r is the ship's Froude number.

4.3 wave-making resistance

The wave-making resistance refers to the force generated by the ship's traveling wave when the ship is sailing in the water, which is the opposite of the ship's forward direction. This paper uses the dimensionless Havelock wave resistance coefficient.

$$C_w = \frac{R_w}{0.5\rho v^2 L^2} = \pi \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} | A(\theta)/L|2cos\theta \times 3d\theta$$

C_w is the wave resistance coefficient; A is the amplitude function; L is the ship length; v is the ship speed; ρ is the water density. According to Nobless' new slender ship theory, the relationship between the wave resistance coefficient and the Froude number can be obtained under the modified condition, as shown in Figure 2.

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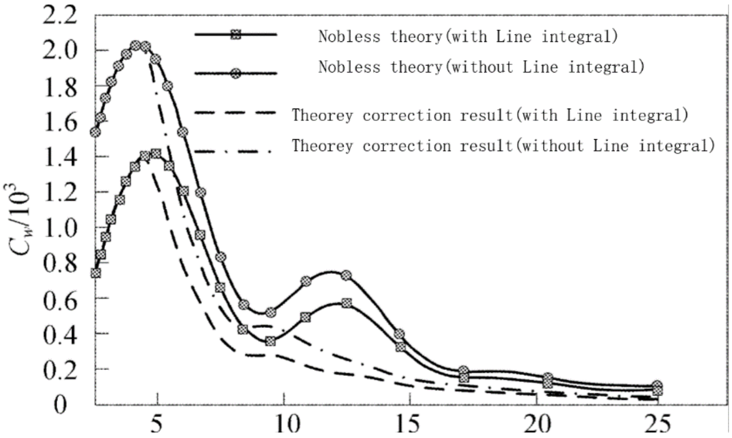

Figure. 2 Wave making resistance considering wave steepness restriction

In the above, the Froude number $F_r \approx 0.13$ is obtained. It can be seen from Figure 2 that the wave resistance coefficient C_w is close to zero, so the wave resistance is negligible here.

4.4 Crushed ice resistance

Colbourne considers the ice flotation resistance and the ice resistance as a whole. the total resistance of the ice area under the condition of crushed ice is divided into open water resistance and crushed ice resistance, and the resistance of broken ice is squared with speed, and the resistance of broken ice And the crushed ice density has a relationship of n power. For different ship types, the value of n is different. Colbourne's formula for estimating total drag under crushed ice conditions:

$$R_T = R_{ow} + R_p$$

$$R_T = 6.9171v^2 + 4.4F_{rp}^{-0.8267}\rho_i gBh_i v^2 C^2$$

$$Fr_p = \frac{v}{\sqrt{gh_iC}}$$

R_T is the total resistance; R_{ow} is the open water resistance; R_p is the crushed ice resistance; V is the speed; F_{rp} is the ice Froude number; ρ_1 is the ice density; g is the gravity acceleration; B is the ship width; h_i is the ice thickness; For crushing ice density.

According to the prediction of the Russian Arctic Research Center, the northeast channel of the Arctic route has dropped from 1.2 m to 1.3 m in 2017-2018 to 0.2 m to 0.6 m in 2024-2025. In the actual voyage of the Arctic route, the ice thickness is generally about 1 m. Therefore, according to the above formula, the actual ice thickness is predicted to be h_i = 1.05 m, 60% crushed ice density and 90% crushed ice density. The total resistance is shown in Figure 3.

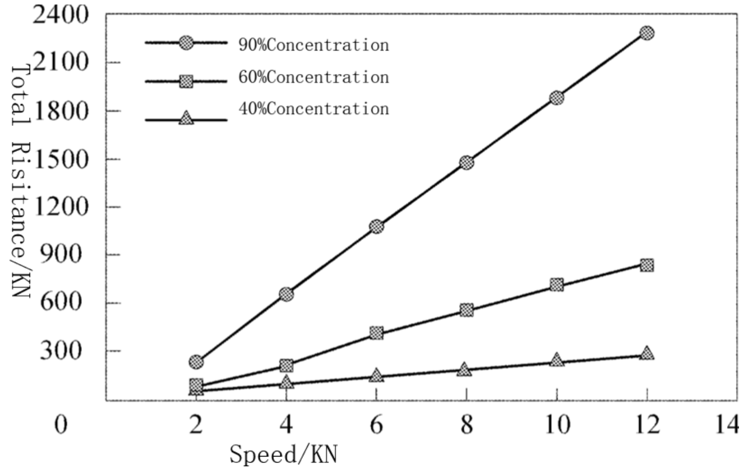

Figure. 3 Total ship resistance curve of a ship with ice thickness of 1.05 m

It can be seen from Figure 3 that under the premise of other conditions, the total resistance of the ship and the speed of the ship change almost linearly. In the actual Arctic route, the density of crushed ice is generally 30%~40%. From this, the total resistance at 40% concentration can be estimated as a function of speed (Figure 3). It can be seen from Figure 3 that the total resistance is 0.23 × 103 kN when the speed is 10 kn.

4.5 The spacing of the bow of the Millennium Wheel

In the ship-following driving of the Arctic route, due to the influence of broken ice, the reverse braking is generally not used, and only the parking brake can be used to follow, and the speed of the ship can be reduced by the sailing resistance. Generally, the speed of the ship is reduced to the minimum residual speed at which the rudder effect can be maintained as the criterion for the completion of the brake. The distance traveled from the start of the firing to the speed of the ship to the minimum residual speed v_0 at which the rudder effect can be maintained is called the parking stroke. The differential equation of ship motion is as follows:

$$(m_s + m_x)a = R$$

$$m_x = 0.07m_s$$

$$a = \frac{R}{m_s + m_x} \approx 0.013m/s^2$$

ms is the total mass of the ship, ms = 23 918 000 kg; mx is the additional water quality of the ship

Normally, the reverse brake is an emergency brake, and the reverse stroke is called the emergency stop distance or the shortest stop distance. Parking brakes are braking behaviors with sufficient safety distance. According to the ship braking distance formula$S_b = \frac{v_n^2 - v_0^2}{2a}$, can get the braking distance is about 1016 m.

Substituting the obtained parameters into the ship's pitch formula,

$$D_{min} = S_m + L_n + 0.51ut_r = 606.98m$$

$$D_{max} = S_m + L_n + 0.51ut_r + S_{b1} = 1521.98m$$

In the actual voyage of the Arctic route, in order to prevent the icebreaker from suddenly hitting the wall, it is often necessary to maintain the maximum d_{max} between the bows and the minimum safe distance the ship should maintain.

5. Conclusion

Normally, the distance from the icebreaker is always based on the requirements of the pilot or estimated by the master's sailing experience. Based on the ship's pitch, the paper establishes a car-following model suitable for the north route. The model gives the calculation method and calculation formula for the following distance and the following speed of the ship sailing in the Arctic route. The calculated "Millennium" wheel sailing resistance and the ship's head spacing are in line with the actual "Millennium" round. The navigation of the Arctic route makes navigation more scientific and safe.

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