Research on Ship Domain in Restricted Waters

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Abstract— **The ship domain refers to a piece of water around the target ship that other ships are not allowed to enter in order to ensure navigation safety. It is widely used in the fields of ship collision avoidance and ship navigation risk assessment. The existing researches on ship domain are mainly focused on open waters, which are relatively fixed and cannot change with the navigation environment in real time. In this paper, factors such as the speed and heading of interfering ships, the distance between the interfering ships and the target ship, the bank effect and interaction effect between ships were analyzed according to the multi-ships encounter situation in the restricted waters. The ship domain which changed in real time with the multi-ships encounter situation in the restricted waters was established to provide a basis for safe navigation of the ship.**

Index Terms—**Multi-ships encounter situation, Restricted waters, Ship domain.**

I. Introduction

The concept of the ship domain was proposed by the Fujii [1] in 1974. He defined the ship domain as the field in which most subsequent ship drivers avoided entering the surrounding area of the previous ship. After conducting multiple observations and statistical analysis on the coastal waters of Japan, Fujii had determined an elliptical ship domain model suitable for narrow waters. After the ship domain model was proposed, it was quickly applied to the research of ship collision avoidance, ship traffic capacity, and water traffic safety evaluation. In the 1970s, Goodwin [2] based on collision avoidance experiments conducted by marine traffic surveys and radar simulators, considering the international collision avoidance rules, then a ship domain model consisting of three sectors was proposed, and its size is related to the ship's length, traffic density, and sea area type. WANG [3]-[4] combined with fuzzy set theory and proposed a fuzzy quaternary ship domain model for space collision risk evaluation. PIETRZYKOWSKI [5] used artificial neural networks to propose a dynamic fuzzy ship domain model, incorporating human experience data and ship factors into the model, but without considering environmental factors. Hansen [6] analyzed the AIS data of ships sailing in the waters of southern Denmark for four years, and Obtained the distance between the ship and other ships or fixed obstacles during navigation, and established the smallest ship domain. Erwin [7] used the method of excluding a certain ship's ratio distance to determine the boundary of the ship domain, thereby establishing different types of ship domain boundaries.

The ship domain research in restricted waters, most of the research focuses on the relationship between the ship domain and the ship's own attributes. In this paper, the multi-ships encounter situation in the restricted waters was analyzed, the factors such as the bank effect and the interaction effect between ships in the restricted waters were considered, according to factors such as the speed, heading and distance of the interference ship, the real-time ship domain will be established according to the different multi-ships encounter situation.

II. Analysis Of Multi-ships Encounter Situation In Restricted Waters

The ship marshalling relationship is composed of dynamic ship entities and has a decisive influence on the collision avoidance behavior of ships. It is time-varying and changes with changes in the navigational conditions of surrounding ships. Due to the limited width of channel in restricted waters, according to the International Regulations for Preventing Collisions at Sea(COLREGs), when a ship is traveling along a channel, it should be as close as possible to the outer edge of the channel on the starboard side of the target ship as long as it is safe and feasible, the position of the target ship in the starboard channel was explained as an example.

The target ship was used as the research subject (as shown in Figure 1). Considering the channel where the target ship was located and the adjacent left channel. The surrounding area of the target ship is divided into front side, rear side, left front side and left rear side based on the position of the front end of the target bow and the characteristics of the restricted water.

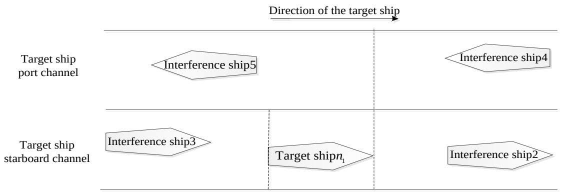

Fig.1 Multi-ships encounter situation in restricted waters

III. Analysis Of Influencing Factors In Ship Domain

A. Analysis of the impact of the interference ship on the target ship domain

The ship domain is not a fixed scope, the size of the ship domain is related to the driving propensity and psychology of the ship's driver, the length, speed, steering performance of the ship, and navigation environment such as traffic density, encounter situation, climate and other factors.Based on previous studies, the ship domain was established considering factors such as the target ship and the interference ship length, speed, the navigation environment.

When encountering two ships in restricted waters, it is necessary to judge the encounter situation and determine the avoidance responsibility of the target ship and the interference ship. In this paper, starting from ship maneuverability, the shortest distance that two ships can avoid collision is the sum of the new course distance of two ships.

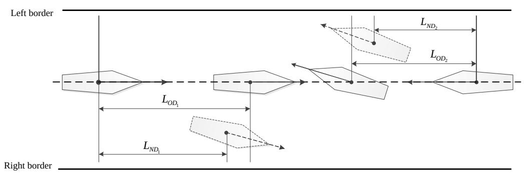

Fig.2 Schematic diagram of ship avoidance

The speed of the target ship before the collision avoidance operation is v_1 , the perception decision response time is t_{m_1} , and the operation response time is t_{s_1} . The speed of the target ship at any time during the operation response time is $v_1(t)$. At $t_{m_1}+t_{s_1}$, the target ship's new course distance can be expressed as:

$$L_{ND1} = v_1 \times t_{m_1} + \int_{t_{m_1}}^{t_{m_1}+t_{s_1}} v_1(t) \times \cos(\varphi_1(t))\, dt \qquad (1)$$

The interference ship's new course distance can be expressed as:

$$L_{ND2} = v_2 \times t_{m_2} + \int_{t_{m_2}}^{t_{m_2}+t_{s_2}} v_2(t) \times \cos(\varphi_2(t))\, dt \qquad (2)$$

B. Analysis of the impact of interaction effect between ships on the ship domain

In restricted waters, in addition to the speed and heading of the target ship and the interference ship, the influence of the interaction effect between ships and the bank effect on the ship domain were also considered.

The interaction effect between ships refers to the phenomenon of deflection or attraction between two ships when the ship passes another ship at a short distance. If the interaction effect between ships is not detected and operated in time, it can easily lead to accidents. Factors affecting the interaction effect between ships: the distance between the two ships, the speed, action time, ship size, water depth.

In this paper, the interaction effect between ships was avoided by the ship control belt width.According to the guidelines of the Permanent International Association of Navigation Congresses (PIANC), the control belt width W_M was calculated.

C. Analysis of the impact of the bank effect on the ship domain

In restricted waters, the bank effect is easy to occur when the ship moves near the bank, which will cause the ship to move sideways or turn. The size of the bank effect is related to the distance between ship and bank, ship speed, ship type and other factors. In this paper, the distance between ship and bank was mainly studied to determine the impact of the bank effect on the target ship. Studies have shown that when the distance between the ship and the bank is greater than 5 times the ship width, the bank effect can be ignored. In this paper, it is stipulated that when distance between ship and bank is greater than 5 times ship width, the bank effect is zero (including 5 times ship width), and the smaller the distance, the greater the bank effect.

The bank distance is the minimum distance to overcome the bank effect when the ship sails near the edge of the control belt. Different bank forms require different bank distances to overcome bank effect. This paper referd to the PIANC guidelines to solve different bank distances.

IV. Ship Domain Modeling

A. Bow semiaxis

In this paper, the target ship domain was constructed when multi-ships encounter. The main influencing factors of the value of the bow semiaxis of the target ship domain were the target ship and the interference ship heading and speed. According to the influence of the interference ship on the target ship domain, the target ship domain was obtained. Since the collision occurs on the hull, to ensure that there was no danger of collision, the influence of the ship type must also be considered.

When the two ships meet, if the new course distance of the interfering ship is smaller than the original course distance, the value of the bow semiaxis is solved as formula:

$$R_{sll} = L_{ND1} + \frac{L_1 + L_2}{2} \quad (3)$$

If the new course distance is not less than the original course distance, the formula is:

$$R_{sll} = L_{ND2} + \frac{L_1 + L_2}{2} \quad (4)$$

Among them, L_0 is the length of the target ship; L_1 is the length of the interference ship.

B. Stern semiaxis

After the encountering, if the ships arrive at the center of each other's ship, the two ships can be artificially considered to have met safely. Therefore, many scholars did not consider the stern semiaxis in detail. In restricted waters, in order to avoid the interaction effect between ships when two ships encounter each other, it was considered that the collision will not end until the two ships pass through each other. So the stern semiaxis was solved in this paper.

After the two ships have passed each other's ships, the confrontation is completed. Therefore, the stern semiaxis is established as:

$$D_{sll_2} = \frac{L_1}{2} \quad (5)$$

When a ship is overtaken, the ship's speed and heading are mainly considered. If there are no special circumstances, as long as the difference between the range of the overtaking vessel and the overtaken vessel after the new course distance is less than the distance between the two ships at the time of the action, no collision accident can be guaranteed. The specific solution is as follows:

$$D_{sll_3} = L_{ND3} - L_{ND1} + \frac{L_1 + L_3}{2} \quad (6)$$

C. Ship left side semiaxis

In this paper, the length of the left side and right side semiaxis in the ship domain was determined by using the width of the control belt, the interaction effect between ships and the bank effect. The target ship sails on the right fairway as an example, the ship left side semiaxis is mainly affected by interference ships. The left side semiaxis can be solved as:

$$D_{el} = \frac{W_M}{2} + \frac{W_b}{2} = \frac{n(L\sin\gamma + B) + W_b}{2} \quad (7)$$

W_b is the distance between the two ships.

If the target ship sails on the left channel, the left side semiaxis is mainly affected by the bank. The left side semiaxis can be solved as:

$$D_{el} = \frac{W_M}{2} + W_q = \frac{n(L\sin\gamma + B)}{2} + W_q \quad (8)$$

Among them: W_q is the bank distance.

D. Ship right side semiaxis

According to the solution method of the left side semiaxis, if the target ship sails on the right channel, the right side semiaxis is mainly affected by the bank effect, so the formula is:

$$D_{er} = \frac{W_M}{2} + W_q = \frac{n(L\sin\gamma + B)}{2} + W_q \quad (9)$$

If the target ship sails on the left channel, the right side semiaxis is mainly affected by the interference ship. The right side semiaxis can be solved as:

$$D_{el} = \frac{W_M}{2} + \frac{W_b}{2} = \frac{n\left(L\sin\gamma + B\right) + W_b}{2} \quad (10)$$

The values of the left side and right side semiaxis are determined based on the surrounding environmental factors of the ship's real-time detection.

V. CONCLUSION

In the restricted waters, considering the ship type, speed, heading, relative distance, bank effect, and interaction effect between ships of the target ship and the interference ship, the target ship domain was established in this paper. Different ship domains can be calculated in real time according to different navigation environments by applying the model proposed in this paper, which provided a theoretical basis for the analysis of ship collision risk and the study of ship collision avoidance decisions.

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