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THE AUTOMATIC COLLISION AVOIDING PLAN RESEARCH OF GIVEN WAY VESSEL IN CROSSING SITUATION

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ABSTRACT

This paper aims to the computing model of quantitative elements in crossing situation based on the separating of different states about vessel's meeting to study the automatic collision-avoiding plan of given way vessel in crossing situation. Following results are proved by simulations: The accuracy of hydrodynamic model is enough for studying and application for automatic collision-avoiding; computing model of quantitative elements by method of bisection is rapidly and reliably convergent during computing. The whole meeting process can be separated to several stages according to the quantitative elements in crossing situation. Different initial collision avoiding measures of given-way vessel in different stages produced as per rules and ordinary practice of seaman.

Keywords: Ship domain; Hydrodynamic model; Crossing situation; Quantitative element in meeting situation; Automatic collision- avoiding

INTRODUCTION

In most traditional automatic collision-avoiding studies, when an automatic collision-avoiding plan or an expert collision-avoiding system is being decided, such an automatic action plan is selected based on such factors as relative bearing and speed of the approaching vessel [1–3], and in some studies, the collision risk index, together with the automatic collision-avoiding plan, is worked out by applying missile guidance, robotic collision-avoiding principle, and so on. Due to insufficient considerations of the impacts of the approaching vessel's course and the current vessel's maneuverability on the collision-avoiding plan as well as the differences in collision-avoiding plans at different meeting stages, the automatic collision-avoiding plans deviate from the collision-avoiding rules and ordinary practice of seamen and largely limited when applied in sailing practice.

According to the connotations, extensions, and generally accepted understandings of the *International Regulations for Preventing Collisions at Sea, 1972* (hereinafter referred to as "the *Rules*"), as for the duration from the moment the two vessels meet each other in a crossing situation at sea to the moment a collision occurs, it can be divided into several stages [4], and different plans should be taken by the give-way vessel at different stages. In sailing practice, pilots take geometric methods to work out and execute collision-avoiding plans based on collision-avoiding rules, ordinary practice of seamen, as well as their own knowledge, skills, experience, and so on. In this process, human beings are intelligent and able to make intelligent decisions and determine collision-avoiding plans for the specific stages according to the situations. But automatic collision avoidance needs to rely on computers, which are not intelligent, to finish the whole process, with judgments being made based on precise division of stages, only after which can the collision-avoiding plans be formulated. Therefore, all stages shall be defined strictly so as to make machine judgments possible. In the meanwhile, quantitative calculations shall be conducted on collision risk, close situation, and immediate danger in a crossing situation. According to the *Rules* and ordinary practice of seamen, this study focused on quantitative calculation models and proposed automatic collision-avoiding plans, in which MMG vessel maneuvering motion model and vessel domain theory were taken as the basis, and definitions or generally accepted understandings of collision risk, close situation, and immediate danger in crossing situations of vessels were applied.

MODELING OF AUTOMATIC COLLISION AVOIDANCE

HYPOTHESES AND DEFINITIONS

Hypothesis 1: The environment where a vessel is maneuvered is open water of a still water environment; according to features of the water, maneuverability of large vessels, and Article VIII of the *Rules*, the hypothesis of avoidance by reducing speed is not considered when the vessel is avoiding collision; no considerations are given to coordinative avoidance; position, course and speed of the approaching vessel are known;

Hypothesis 2: No considerations are given to the effects of roll, pitch, or heave;

Definition 1: Current Vessel/Approaching Vessel: give-way vessel/stand-on vessel in a crossing situation.

Definition 2: Vessel Domain and Arena: the definitions of References [5, 6] are adopted.

Definition 3: Close Situation: In such a situation, the approaching vessel will also enter the domain of the current vessel when the current vessel makes a turn by putting the rudder fully right. At a certain time or position point, the close situation generates a critical point where the current vessel makes a turn by putting the rudder fully right and the approaching vessel is tangent to the boundary of the current vessel's domain.

Definition 4: Time to Close Situation (TCS): The duration between the current moment and PCSF.

Definition 5: Collision Risk, referring to a situation under the following conditions: 1) with speed and course being kept, the approaching vessel enters in the domain of the current vessel; 2) the approaching vessel enters in the arena of the current vessel; 3) TCS≤20 minutes. Final Collision Risk refers to a risk that the two vessels will collide finally with unchanged speed and course no matter whether currently there is a collision risk or not.

Definition 6: Immediate Danger refers to the situation that the two vessels will also collide even if the current vessel makes a turn by putting the rudder fully right. Point Immediate Danger Formed (PIDF) refers to the last point before which the two vessels will avoid collision if the current vessel turns right by putting the rudder fully right. Collision refers to that the distance between the centers of gravity of the two vessels is less than half of the sum of two vessels' lengths.

Definition 7: Time to Immediate Danger (TID): The period between the current moment and the point immediate danger formed.

ANALYSIS OF VESSELS' MEETING SITUATIONS

The period from the meeting of two vessels at sea to their collision can be divided into the following stages [4]:

1) Free sailing stage before a collision risk forms;
2) Stage from the point collision risk forms to the point close situation forms;
3) Stage from the point close situation forms to the point immediate danger forms;
4) Stage from the point immediate danger forms to the occurrence of a collision.

MODELING FOR QUANTITATIVE CALCULATIONS OF ELEMENTS OF COLLISION-AVOIDING SITUATIONS

COORDINATE SYSTEM

To make calculations easy, the coordinate system shown in Fig. 1. is used in this paper:

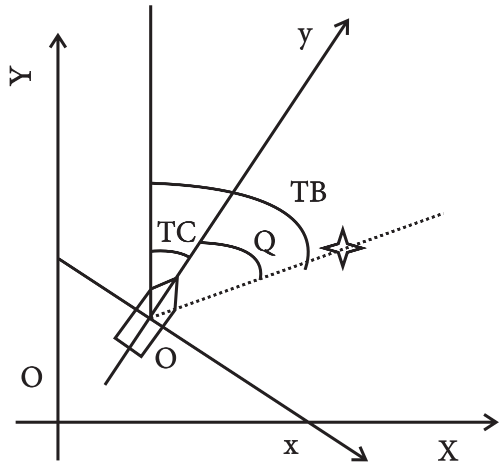

Fig. 1. Coordinate system

1) XOY is the earth-fixed coordinate system, where the positive Y-axis points North, and the positive X-axis points East, with right as the positive direction;
2) XOY is the vessel moving coordinate system, where the positive y-axis points bow, and the positive x-axis point's starboard, with right as the positive direction;

The angle between the two coordinate systems is the current vessel's course TC, which has the following relations with the object's bearing TB and the relative bearing Q:

$$TB = Q + TC \quad (1)$$

Coordinate transformation relations:

$$[X, Y] = [x, y] * \begin{Vmatrix} \cos(TC) & -\sin(TC) \\ \sin(TC) & \cos(TC) \end{Vmatrix} \quad (2)$$

According to the simulation process, this coordinate system, more suitable for sailing practice, has more advantages over other coordinate systems.

VESSEL DOMAIN MODEL

According to References [5–8], an off-centering circular vessel domain model is used as the vessel domain model.

The center of the circle of the vessel domain is where the virtual vessel is located, and the real vessel is on the left rear of the virtual vessel. Radius of vessel domain, offset of real vessel position from the center of vessel domain, and other parameters can be selected according to different vessel features, sailing environments, and so on. The simulation object in this paper was a 76,000 DWT full loaded bulk carrier, of which the radius R in the open water was considered as 6 times of the ship length, the off-centering direction was 199°, and the distance was 3 times of ship length.

VESSEL MOTION MODEL

Since the studies of pitch, heave and roll in the collision-avoiding process had only limited significance, studies were only performed on motions of the ship in longitudinal, transverse and yaw directions in still water. Thus MMG three-degree-of-freedom vessel motion model was adopted in this paper. Details about the meanings of symbols in the equation are described in References [9–10].

$$\begin{cases} (m + m_y)\dot{u} - (m + m_y)\, vr = y_H + y_P + y_R + y_F \\ (m + m_x)\dot{v} - (m + m_x)ur = x_H + x_P + x_R + x_F \\ (I_{ZZ} + J_{ZZ})\dot{r} = N_H + N_R + N_F \end{cases} \quad (3)$$

Through transformation and processing of the above equation of motion, eventually forces, moments, accelerations, angular accelerations, velocities, and angular velocities were expressed as functions of time t. Vessel coordinates were calculated based on the above model, with Runge-Kutta method being adopted.

QUANTITATIVE CALCULATION MODEL FOR COLLISION-AVOIDING ELEMENTS

QUANTITATIVE CALCULATION OF PCSF

Suppose the distance from another ship to the boundary in the direction of the vessel domain center is Dis at the moment t when the current situation begins; the time of putting the rudder fully right is tm; and thus, Dis is a function of the two variables of t and tm. To find the solution of PCSF is to find $t_m = t_m^0$ satisfactory to the conditions that: when the vessel starts to sail at initial speed and on initial course from the current moment, the vessel is kept putting the rudder fully right to make a turn, and the approaching vessel is tangent to the domain of the current vessel. Thus, it is to find the solution of $t_m = t_m^0$:

$$\min\left(\underset{t_m = t_m^0}{\text{Dis}}\right) = \min\left(f(t, t_m^0)\right) = 0 \quad (4)$$

Specific expression of the function Dis=f(t,t_m)

$$\begin{cases} \text{Dis}^t = \left\|(X_0^t - X_R^t)^2 + (Y_0^t - Y_R^t)^2\right\|^{0.5} - R \\ X_0^t = x_0^t + 0.25R_{\text{lingyu}} \cdot \sin(TC_0^t + 19) \\ Y_0^t = y_0^t + 0.25R_{\text{lingyu}} \cdot \sin(TC_0^t + 19) \end{cases} \quad (5)$$

(X_R^t, Y_R^t) is determined by the following equation:

$$(X_R^t, Y_R^t) = (X_R^0, Y_R^0) + \left(\sin(TC_R), \cos(TC_R)\right) * t * v_R \quad (6)$$

If t≤t_m, then:

$$(x_0^t, y_0^t) = (x_0^0, y_0^0) + \left(\sin(TC_0), \cos(TC_0)\right) * t * v_0 \quad (7)$$

If t>t_m, then:

Taking $\left(x_0^{t_m}, y_0^{t_m}\right)$ as the initial condition, as the time, and rudder angle as 35°, (x_0^t, y_0^t) is calculated as per according to equation (3). R is the radius of the vessel domain circle.

Superscript t represents the moment t; subscript 0 represents the current vessel, and R represents the approaching vessel; v represents the speed, and TC represents the course; (x, y) and (X_R, Y_R) are the center of the current vessel's domain and the position of the approaching vessel.

Judging from the physical significance of the problem, Dis=f(t,t_m) has the following attributes:

1) When $\exists t_1 > 0, t_2 > 0, t_m \in [t_m^0 - t_1, t_m^0 + t_2], \min\left(f(t, t_m)\right)$ decreases monotonically;
2) If the approaching vessel is far away and it will eventually enter in the domain of the current vessel if not steered, therefore $\min\left(f(t,0)\right) > 0$, $\min\left(f(t, TCPA)\right) < 0$;
3) $\min\left(f(t, t_m^0)\right) = 0$ has just one solution in $t_m^0 \in [0, TCPA]$ therefore, bisection method can be used to find the solution of t_m^0. The specific method is shown in the simulation calculation process.

QUANTITATIVE CALCULATION OF PIDF

Same as PCSF, a mathematical model was built for PIDF, with the vessel domain being changed into a circular area centered on the current vessel's center of gravity, with the radius being half of the sum of the two vessels' lengths.

COLLISION RISK

For judging whether there will be a final collision risk or not, the criterion is to see whether the approaching vessel will enter in the domain of the approaching vessel or not. Thus, with course and speed being kept, the conclusion can be reached based on the distance from the approaching vessel to the boundary of the vessel domain in the direction of the vessel domain center at different moments, namely, Dis=f(t)=D(t)−R, in which D(t) represents the distance from the vessel domain center to the approaching vessel at moment t. If its minimum value: $\min\left(f(t)\right) \leq 0$, it means that at some moment, the approaching vessel enters the vessel domain and there will be a final collision risk; if TCS≤20 min and the approaching vessel is in the arena of the current vessel, a collision risk forms; if $\min\left(f(t)\right) \geq 0$, and the approaching vessel does not enter the domain of the current vessel, there will be no final collision risk.

COLLISION-AVOIDING PLANS OF THE GIVE-WAY VESSEL IN A CROSSING SITUATION

According to the time points determined based on element definitions and numerical solutions in a crossing situation, the crossing situation was divided into different stages, and the corresponding avoiding measures to be taken were analyzed as follow.

If there is no final collision risk, no plan needs to be executed. Otherwise,

(a) Stage 1, a collision risk has not formed. An early avoiding plan can be executed freely (leftward or rightward).
(b) Stage 2, a collision risk has formed but a close situation has not formed. Making a right turn can ensure the vessels pass

by each other at a safe distance, and therefore, according to the responsibility clauses and the generally accepted understandings about actions deviating from the *Rules*: if taking an action as per the *Rules* can avoid an immediate danger, the *Rules* shall be followed, and the procedures shall specify that the ship shall make a right turn.

(c) Stage 3, a close situation has formed, an imminent danger has not formed, and a sharp turn to the right cannot ensure the vessels pass by each other at a safe distance. According to the responsibility clauses, both vessels shall deviate from the *Rules* so as to avoid the immediate danger, if necessary. According to the Collision-avoiding Rule 17, Action by Stand-on Vessel, when a stand-on vessel take actions alone, it shall avoid turning left when meeting a vessel on its own port side: if it can pass by the other vessel at a safe distance when turning left, it shall deviate from the rule and turn left to the largest extent and even turn round so that the collision can be avoided; if turning left cannot make it pass by the other at a safe distance either, the direction of avoidance shall be decided through comparison between the shortest distances from it to the approaching vessel in the cases of left and right full rudders.

(d) Stage 4, an imminent danger has formed, at which stage, the action most helpful in avoiding the collision shall be taken, and meanwhile, whether the vessel makes a turn to the starboard side or the port side should be determined based on the shortest distances in the two collision avoidance cases of turning right and left respectively.

SIMULATION CALCULATION

SIMULATION DIGITAL VESSEL MODEL DESIGN

With the vessel in Section 2.2 as the simulation object, MATLAB programming was used to check the precision of the digital model. Comparison was made among full rudder maneuverings at different rotational speeds and at full speed respectively (as shown in Tab. 1.). According to the results, the vessel speed performance and maneuverability of the digital vessel model could be very close to those of a real vessel by adjusting different factors.

Tab. 1. Speed compare of MMG model and ship

Rotational Speed (rpm) / Speed (Kn)	77.7	84.9	92.2	99.8
Hydrodynamic model	10.7	12.0	13.2	14.3
Real vessel (vessel model)	11.0	12.0	13.0	14.0

DESIGN OF SIMULATION PROCEDURES

Digital simulation was conducted with the vessel in Section 2.2 as the simulation object. Initial conditions: target vessel: relative bearing: 045°, distance: 5.6 nautical miles, speed: 12 kn, and course: 270°; current vessel: initial speed: 12 kn, and course: 000°. Output results: a close situation formed at 5513 m / 919 s. Immediate danger formed at 1097 s / 6584 m.

PROCEDURES OF JUDGING THE STAGES OF THE GIVE-WAY VESSEL IN A CROSSING SITUATION

In this paper, with translation of central arena being done according to Reference [6], the radius was 2.7 nautical miles, offset of the center was 1.9 nautical miles, and the bearing was a relative bearing of 199°. Under the conditions that for the target vessel, the relative bearing was 045°, the distance was 5.656 nautical miles, speed was 6m/s, and course was 270°, and for the current vessel, the initial speed was 6m/s and the course was 000°, a simulation was conducted, and the calculation results were output as follows:

1) TCS<20 min;
2) DCPA=0, TCPA=1234.7s;
3) there would be a final collision risk;
4) when TRC=644, and DRC=3864, the approaching vessel entered the arena;
5) the approaching vessel was outside the arena and there would not be a collision risk for now.

CONCLUSIONS

According to the simulation results, the mathematical model used in this study was reliable, and the algorithm would converge fast and reliably when a small value (5m) was taken by using the bisection method; the precision met the requirement of automatic collision-avoiding studies and sailing practice of vessels. The study results provided collision avoidance plans for different stages of the give-way vessel in a crossing situation. A complex sailing model, which was a combination of this model and the steering model, could develop possible collision-avoiding plans specific to different time points, optimize all plans, and eventually determine the optimal automatic collision-avoiding plans suitable for collision-avoiding rules and ordinary practice of seamen.

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REFERENCES

1. Zhongyi Zheng. *Research on automatic collision avoidance decision-making system of ships* [D], Dalian maritime university, 2000.

2. *The discuss on automatic collision avoiding decision for Muti-ships* [J].Joural of NANTONG VOCATIONAL & TECHNICAL SHIPPING COLLEGE, Vol 4, No 3, Feb. 2005, pp. 52–53, 81.

3. Ming-Cheng Tsou. Chao-Kuang Hsueh, THE STUDY OF SHIP COLLISION AVOIDANCE [J]. Journal of Marine Science and Technology, Vol. 18, No. 5, pp. 746–756, 2010.

4. A.N. cockcroft, J.N.F. la major. *Guidelines for the rules of navigation.* Fourth edition [M]. Dalian: Dalian maritime institute press. 1992.132-134.

5. Goodwin, E. M. *A statistical study of ship domains.* [J]. Journal of Navigation, 28, 328, 1971.

6. DAVIS P V, DOVE M J, STOCKEL C T. *A computer simulation of marine traffic using domains and arenas* [J]. Journal of Navigation, 1980, 33: 215-222.

7. QI Le, ZHENG Zhongyi, Li Gouping. *AIS-data based ship domain of ships in sight of one another.* [J].Journal of Dalian Maritime University Vol 37, No 1, Feb. 2011, pp. 48–50

8. R. Szlapczynski, *Solving Multi-Ship Encounter Situations by Evolutionary Sets of Cooperating Trajectories* [J].TRANSNAV, Volume 4, Number 2, 2010.

9. Li Wenkui, Chen Yongbing, Tian Weifeng et al. *Real-time simulation of ship motion control based on MATLAB* [J]. Journal of system simulation, volume 19, 19, October, 2007.4424-4427, 4433.

10. Y. Yavin, C, Frangos. *Computation of Feasible Control Trajectories for the Navigation of a ship around an Obstacle in the Presence of a Sea Current* [J]. Mathl. Comput. Modelling Vol. 21, No 3, 1995, pp. 99–117.

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