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Research on Double Collision Avoidance Mechanism of Ships at Sea

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ABSTRACT: When two power driven vessels encounter at sea so as to involve risk of collision, they need to avoid collision effectively. The concept of Right Ship may mislead this ship's officers thinking his or her direct navigating has absolute power with this special ship. This paper will define DCPA symbols; give the cause and the method of double collision avoidance mechanism of ships at sea.

1 CLOSE-QUARTER SITUATION DISTANCE AND IMMEDIATE DANGER DISTANCE

The understanding of the terms such as "close quarter situation" and "immediate danger" is very important to ship's officers. How to use them correctly is still a question not quite well answered.

The distance of close quarter situation (Dclose) is defined as an action taking distance to a target ship, when own ship takes a large altering course (such as 90°) to avoid collision with the target ship, which can make own ship pass the target ship at the minimum safety distance.

The distance of immediate danger (Dcollid) is defined as an action taking distance to a target ship, at which own ship can't avoid collide with the target ship based on own ship alone altering course action.

This paper will discuss own ship's relative motion to a target ship and define DCPA as plus or minus. When the target ship is on the left side of relative motion track, define DCPA as "positive". When the target ship is on the right side of the relative motion track, define DCPA as "negative".

1.1 *The ship motion mathematical models*

As shown in figure 1, O and T represent respectively the own ship and the target ship. Let the velocity and course of own ship as the V_0 and the C_0 respectively, the velocity and course of the target ship are V_1 and C_1 respectively, azimuth for B, distance for $Dist$, $\overrightarrow{CA} = V_1$. So, the relative velocity V_{01} and relative course C_{01} of own ship to target ship, will show respectively as follows [1, 2, and 3]:

$$V_x = V_0 \times \sin(C_0) + V_1 \times \sin(C_1 + \pi) \quad (1)$$

$$V_y = V_0 \times \cos(C_0) + V_1 \times \cos(C_1 + \pi) \quad (2)$$

$$C_{01} = \begin{cases} tg^{-1}(V_x / V_y) & (V_x \geq 0, V_y > 0) \\ 90 & (V_x > 0, V_y = 0) \\ 180 + tg^{-1}(V_x / V_y) & (V_y < 0) \\ 270 & (V_x < 0, V_y = 0) \\ 360 + tg^{-1}(V_x / V_y) & (V_x < 0, V_y > 0) \\ nil & (V_x = 0, V_y = 0) \end{cases} \quad (3)$$

$$V_{01} = (V_x^{\,2} + V_y^{\,2})^{1/2} \quad (4)$$

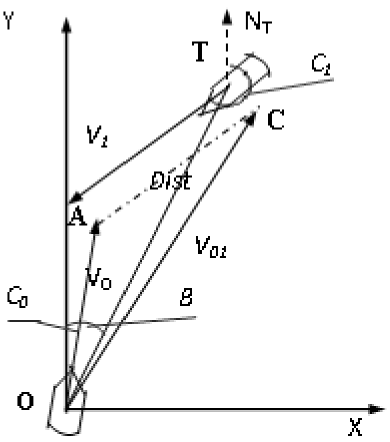

Figure 1. Own ship's relative motion

DCPA (distance of the closest point of approach) and *TCPA* (time to closest point of approach) will show respectively as follows [1]:

$$DCPA = Dist \times \sin(C_{01} - B) \tag{5}$$

$$TCPA = \frac{Dist \times \cos(C_{01} - B)}{V_{01}} \tag{6}$$

1.2 *The distance of close-quarter situation*

As shown in figure 2, let safety encounter distance be *DSPA*, namely the radius of the circle T in this figure, the turning radius of own ship be *R*. When own ship arrive at point A in relative motion to the target ship, it begin to give way altering course to starboard. The own ship will get to point E in this course after double ship's length which is called the lag distance. The own ship begin turning from point E, reached point E_1 in true motion on the turning circle H, while target ship along her course C_1 to get point T_1. The own ship turning circle H tangents the target ship safety encounter distance T_1 at point E_1. So, segment AT is the distance of close-quarter situation show as D. This close-quarter situation distance can be calculated by the relative motion equation of own ship.

Let the cycle of own ship's turning circle under full rudder be t_0 minutes, turning angular velocity be ω, the own ship takes t_0 minutes completing relative movement to the target from point O to point E. Then the own ship by turning movement from the point E to the point E_1, at this time the target ship carrying safety distance circle move in linear from point T to point T_1, it takes time interval of t_1 - t_0, the turning circle radius (*R*) is generally double the ship's length, then

$$\omega = \frac{2 \cdot \pi}{T_0} \tag{7}$$

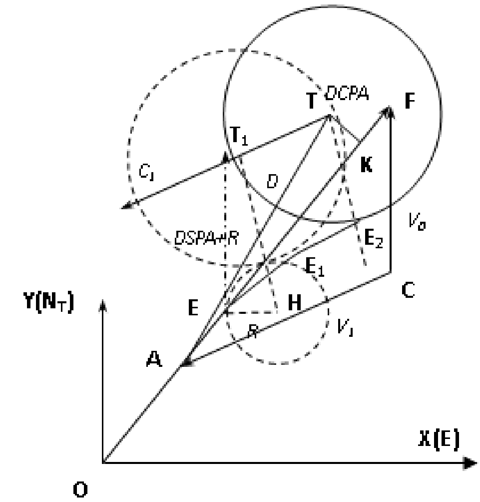

Figure 2. The distance to target ship in close-quarter situation

In Cartesian coordinate system XOY, the relative motion trajectory equation of own ship from point O (*t = 0*), then passing E ($t = t_0$), to the point E_2 ($t = t_1$) can be expressed as follows.

$$\begin{bmatrix} X \\ Y \end{bmatrix} = R \cdot \begin{bmatrix} 1-\cos(\omega(t-t_0)) & \sin(\omega(t-t_0)) \\ \sin(\omega(t-t_0)) & \cos(\omega(t-t_0))-1 \end{bmatrix} \begin{bmatrix} \cos(C_0) \\ \sin(C_0) \end{bmatrix} + \begin{bmatrix} V_1(t_0-t) & V_{01}t_0 \\ V_1(t_0-t) & V_{01}t_0 \end{bmatrix} \begin{bmatrix} \sin(C_1) \\ \sin(C_{01}) \end{bmatrix} \tag{8}$$

$$DSPA^2 = (X_{t=t_1} - Dist \cdot \sin(B))^2 + (Y_{t=t_1} - Dist \cdot \cos(B))^2 \tag{9}$$

Decoding formula (7) - (9), making the ship's distance to the target at the tangent point E_1 equal to the safety encounter distance, we can get t_0 and t_1, so we can solve the close-quarter situation distance (Dclose = D).

$$D = (DCPA^2 + (V_{01} \cdot (TCPA - t_0 + \frac{2 \cdot L_0}{V_0}))^2)^{1/2} \tag{10}$$

The own ship's maximum altering course to the right will be as follow.

$$\Delta C = \frac{2 \cdot \pi \cdot (t_1 - t_0)}{T_0} \tag{11}$$

In the same way, considering the own ship as a one point, the extent of the target ship will expand to the sum of two ship's length, $L_0 + L_1$, replace it with the *DSPA* in formula (9), we can get the collision distance (Dcollid = *D*) and the own ship's maximum altering course to starboard. If the length of the target ship is unknown, we can take a desirable L_1 = 330 m to get a conservative estimate collision distance.

2 EXAMPLES

2.1 *The action of give-way ship*

Let own ship length be L_0=190 m, velocity and course as V_0=16 kns and C_0=000° respectively, velocity and course of the target ship are respectively V_1=18 kns, C_1=240°, the azimuth of target ship is B=30°, distance D=8 nautical miles.

So, according to the formula above, we can get owe ship's relative speed to the target ship V_{01}=29.5 knots, the relative course C_{01}=32°.0. Target ship is located on the left side of the relative movement line, the $DCPA$=+0.27n miles, the $TCPA$=16.3 minutes.

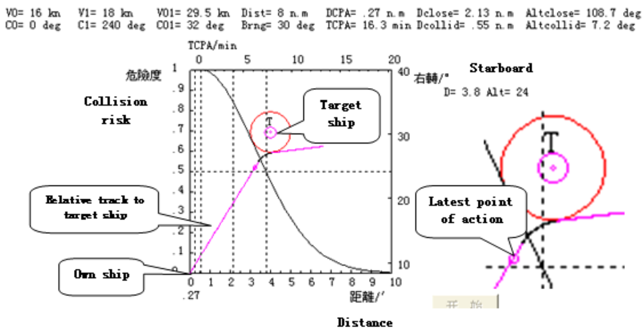

Figure 3. The collision risk and relative motion to target of give-way ship

Taking $DSPA$=1.0 nautical miles, let the sum of the two ship length be the maximum, L_0+L_1= 190+330= 520m= 0.28 nautical miles, the turning circle radius (R) be double the ship's length, 380m=0.21 nautical miles, the period of own ship turning circle be 5 minutes, we can calculate the close-quarter situation distance $Dclose$=2.13 nautical miles, at that point own ship will alter course 2 ° to starboard side, we can also calculate the collision distance $Dcollid$=0.59 nautical miles, at that point own ship should alter course 7°.2 to starboard side to avoid collision.

Another curve in the figure is collision risk curve. This curve can be used to determine collision avoidance opportunity and the value of the collision avoidance action. For this example the opportunity of action taking is 3.8 nautical miles from the target ship, the action value is altering course 24 ° to starboard.

2.2 *The action of stand-on ship*

Let own ship length be L_0=190 m, velocity and course as V_0=18 kns and C_0=240° respectively, velocity and course of the target ship are respectively V_1=16 kns, C_1=000°, the azimuth of target ship is B=210°, distance D=8 nautical miles.

So, according to the formula above, we can get owe ship's relative speed to the target ship V_{01}=29.5 knots, the relative course C_{01}=212°.0. Target ship is located on the left side of the relative movement line, the $DCPA$=+0.27 n miles, the $TCPA$=16.3 minutes.

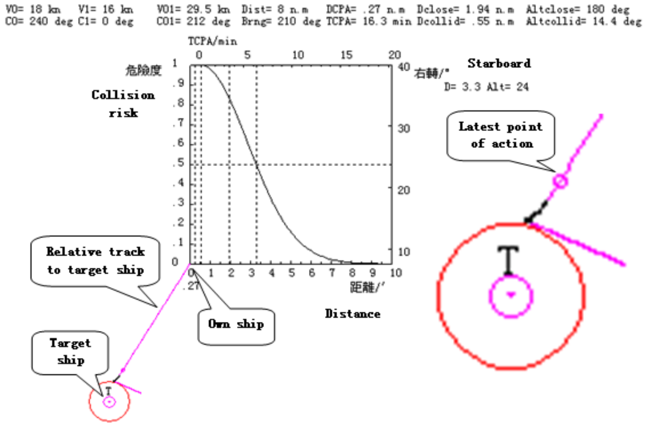

Figure 4. The collision risk and relative motion to target of stand-on ship

Taking DSPA=1.0 nautical miles, let the sum of the two ship length be the maximum, L_0+L_1= 190+330= 520m= 0.28 nautical miles, the turning circle radius (R) be double the ship's length, 380m=0.21 nautical miles, the period of own ship turning circle be 5 minutes, we can calculate the close-quarter situation distance $Dclose$=1.94 nautical miles, at that point own ship will alter course 180° to starboard side, we can also calculate the collision distance $Dcollid$=0.55 nautical miles, at that point own ship should alter course 14°.4 to starboard side to avoid collision. The opportunity of action taking is 3.3 nautical miles from the target ship; the action value is altering course 24 ° to starboard.

3 THE RELATIONSHIP BETWEEN THESE TWO DISTANCES

In case of crossing situation, the distance of close-quarter situation of give-way ship is greater than that of the stand-on ship. In the case above it is about 0.19 nautical miles, which is equivalent to 23 seconds. The minimum limit of the give-way ship's collision avoidance action must not drag to the close-quarter situation distance in order to give stand-on ship enough time to take necessary action alone. Based on the above example, taking different bearings of target ship, we get a set of numerical simulation; the results of own ship's action as give-way ship are shown in table 1.

Table 1. Crossing simulation calculation give-way ship's action, (safety passing distance $DSPA=1'.0$, $V_1=18$, $C_1=240$, $D=8.0$, $V_{01}=29.5$, $C_{01}=32$, $TCPA=16.3$)

No.	Target ship		Own ship (give-way ship) action					
	B	*DCPA*	*Dclose*	ΔC_0	*Dcollid*	ΔC_0	*Dact*	ΔC_0
1	28	0.55	1.89	81.4	-	-	2.9	20
2	29	0.41	2.02	95.0	-	-	3.2	23
3	30	0.27	2.13	108.7	0.59	7.2	3.8	24
4	31	0.13	2.21	113.8	0.96	50.4	4.1	27
5	32	-0.01	2.29	126.7	1.15	72	4.2	30
6	33	-0.15	2.35	137.5	1.19	93.6	4.5	32
7	34	-0.29	2.40	153.4	-	-	4.7	34

Also, considering the stand-on ship taking action alone, taking different bearings of target ship, we get a set of numerical simulation; the results of own ship's action as stand-on ship are shown in table 2.

Table 2. Crossing simulation calculation stand-on ship's action, (safety passing distance $DSPA=1'.0$, $V_1=16$, $C_1=0$, $D=8.0$, $V_{01}=29.5$, $C_{01}=212$, $TCPA=16.3$)

No.	Target ship		Own ship	(stand-on ship)		action		
	B	*DCPA*	*Dclose*	ΔC_0	*Dcollid*	ΔC_0	*Dact*	ΔC_0
1	208	0.55	1.83	177.8	-	-	2.8	18
2	209	0.41	1.90	178.6	-	-	3.0	21
3	210	0.27	1.94	180.0	0.55	14.4	3.3	24
4	211	0.13	1.97	175.0	0.96	172.8	3.6	26
5	212	-0.01	1.99	112.3	1.01	93.6	3.8	28
6	213	-0.15	1.99	108.0	1.01	86.4	4.2	29
7	214	-0.29	1.98	108.7	-	-	4.4	31

Comparing the collision avoidance action results in table 1 and table 2, the give-way ship's distance of close-quarter situation is longer 0.06 to 0.42 miles than that of the stand-on ship, which is equivalent to 7 to 51 seconds. The duty officer on the give-way ship should fully consider the stand-on ship officer's psychology bearing ability and take early collision avoidance action.

Also, we can get the result that the distance of give-way ship's close-quarter situation is larger 1.16 to 1.46 miles than its collision distance. Such a short time interval will not allow the officer take any hesitation and require him or her in a timely manner to make correct collision avoidance decision-making and take direct actions.

4 CONCEPT OF DOUBLE COLLISION AVOIDANCE AND CLOSE-QUARTER SITUATION

Ship's collision segments will include the free navigation at a distance, risk of collision, close-quarter situation, imminent danger and collision [5, 6]. From late segment of the risk of collision to the early segment close-quarter situation is the forming phase of close-quarter situation and is the most important moment of the manipulating action alone for the two ships. After the two ships coordinated action, by avoiding the close-quarter situation, these two ships can pass in a safety distance and can sufficiently avoid collision.

In rule 8 Action to avoid Collision paragraph (a), the minimum limit of "ample time" should be not to form the close-quarter situation. The stand-on ship "may however take action to avoid collision by her manoeuvre alone" is the key of not let the vessels fall in close-quarter situation. Since then, there is no more absolute Right route for the stand-on ship. The stand-on ship must bear the obligation of action alone to avoid close-quarter situation. The concept of "double collision avoidance" in the modified collision regulations has been clearly revealed which requires ship officers to have clear quantitative distance figures.

The key step and the first priority of establishing practice for preventing collision at sea are to avoid close-quarter situation. The outlook, judgment, decision-making, action and validation segments should be around this first priority so as to grasp the crucial point of collision avoidance. If this concept becomes common cognitive and widely be used, more and more ship manipulations could lead to safe pass in a desirable distance.

5 CONCLUSION

Through calculating the distance of close-quarter situation, we find that the action of give-way vessel is easier to achieve the desired effect of collision avoidance than that of the stand-on ship. We suggest that the give-way vessel's collision avoidance action should be strictly observed to make it not lose the good anti-collision opportunity. In fact, all ships are responsible to ensure navigation safety and protection of the marine environment and are the main part of the obligations. The division of stand-on ship and give-way ship by the collision avoidance rules is only the division of obligation for collision avoidance and not to exempt the stand-on ship from liability of complying with the obligations. The give-way vessel, however, should fully recognize her own advantages, give the stand-on ship more behavior space and relieve the psychological pressure of stand-on ship officer. Because the purpose of practice for preventing collision at sea is to avoid close-quarter situation, we should advocates the concept of "double collision avoidance". Estimating the close-quarter situation distance and the immediate danger distance correctly will help the navigator fully understand the process of collision avoidance and take correct collision avoidance action in a timely manner. This massage, no doubt, will increase the navigator's responsibility and self-confidence of anti-collision manipulation and will be the basis of analyzing specific encounter situation and collision avoidance decision-making.

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