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MODEL OF OPTIMAL COLLISION AVOIDANCE MANOEUVRE ON THE BASIS OF ELECTRONIC DATA COLLECTION

ABSTRACT

The results of the data analyses show that accidents mostly include damages to the ship's hull and collisions. Generally all accidents of ships can be divided into two basic categories. First, accidents in which measures for damage control should be taken immediately, and second, those which require a little more patient reaction. The very fact that collisions belong to the first category provided the incentive for writing the current paper.

The proposed model of optimal collision avoidance manoeuvre of ships on the basis of electronic data collection was made by means of the navigation simulator NTPRO – 1000, Transas manufacturer, Russian Federation.

KEY WORDS

safety at sea, Collision Avoidance System, starting point of collision avoidance manoeuvre

1. INTRODUCTION

Collision of ships is the most frequent accident in modern navigation. Provision of up-to-date navigational equipment does not automatically mean fewer collisions. As a matter of fact, there are more collisions because the number of vessels is constantly increasing. Due to the increased traffic density vessels meet at shorter distances, so they have very little time and space left for appropriate collision avoidance manoeuvre.

The Collision Avoidance Rules themselves do not represent sufficient guarantee for avoiding collisions, since the researches of human factor showed that 10% of all collisions were caused by non compliance with the Rules and 90% by other human errors. Furthermore, collisions are basically not caused by inadequate interpretations of the Rules, but above all, by wrong interpretations of the situations taking place at sea. This is the consequence of insufficient training on RADAR and Automatic Radar Plotting Aids, and particularly of misinterpretation of the results of radar plotting procedures.

The aim of the paper is to work out a safe and controlled collision avoidance manoeuvre, which complies with the Collision Avoidance Rules and is efficiently applied in navigation at sea. It also aims to enhance the safety of merchant shipping in general.

2. THEORETICAL PART

Radar plotting is a graphical display of the movements of objects observed on the radar screen and plotted on the radar diagram.

Radar plotting is used to:

- avoid collisions at sea during voyage by altering own ship course,
- avoid collisions at sea during voyage by altering own ship speed,
- avoid collisions at sea during voyage by altering own ship course and speed,
- calculate the course (Kt) and speed (bt) of the observed target vessel,
- predict manoeuvres of observed ships.

Two types of radar plotting are distinguished:

- relative,
- absolute.

2.1. RELATIVE RADAR PLOTTING

In relative radar plotting we are first interested in the course and speed of the observed vessel that can be obtained from the vector triangle of speed, see Figure 1.

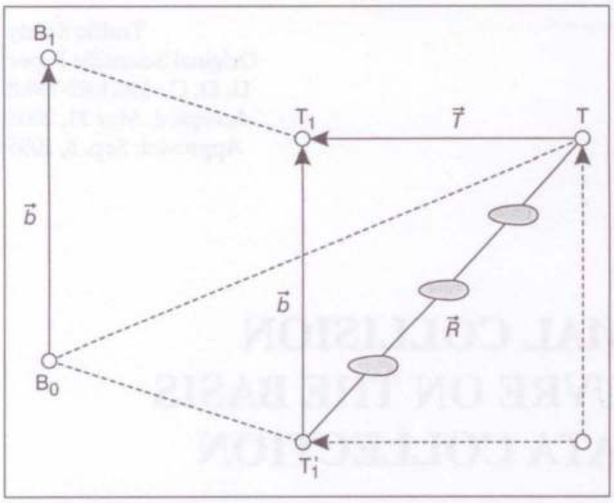

Figure 1 - Relative and Absolute Radar Plotting

2.2. COLLISION COURSE

If observing the relative vector $\vec{R}$, we see that the collision situation takes place when the relative vector passes through own ship or the centre of the radar screen, see Figure 2.

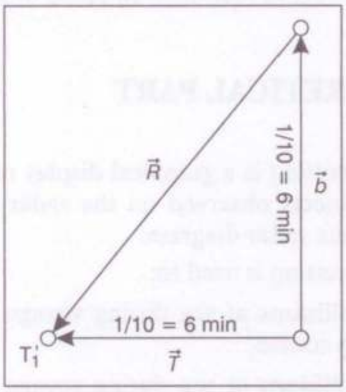

Figure 2 - Vector triangle of speed

In both cases the bearing of the observed ship does not alter and the distance decreases.

The avoidance manoeuvre can be carried out in three ways:

- by altering the course at the same speed,
- by altering the speed at the same course,
- by altering both the speed and the course.

In principle we avoid collisions at high seas by altering the course at the same speed, whereas altering the speed at the same course is applied in areas where manoeuvring space is limited and where the engine is in the standby position. In such a case the speed is decreased. Collision avoidance by altering both the course and the speed is applied only in exceptional circumstances.

2.3. MANOEUVRING TIME (MT)

The collision avoidance manoeuvre should be carried out instantaneously in time determined with the Action Point Time (APT). In such case mathematical calculations of our vector triangle will be accurate. Because of the ship's inertia, her course and speed cannot be altered momentarily. Therefore, the manoeuvre of altering the course and the speed should start a little before APT and finish a little after APT. Thus, presuming a linear alteration of the course or the speed, APT would fall in the middle of the manoeuvre.

Some nautical tables give values "X" in metres, for which we have to start the manoeuvre of altering course K_1, so that the ship will be on course K_2 after the manoeuvre. From the tables we obtain value X with the arguments $\Delta K = K2 - K1$ and the radius of the turning circle, which differs with each ship and speed. The way of determining the starting point of the manoeuvre with value X is shown in Figure 3.

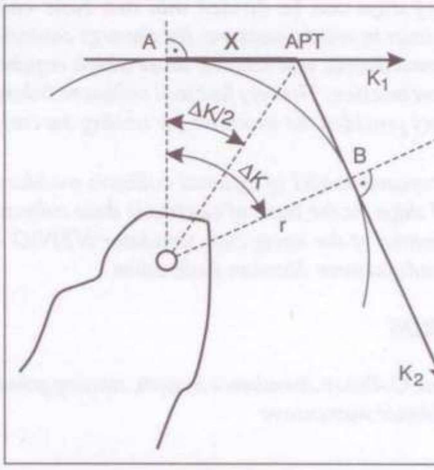

Figure 3 - Determining the start of manoeuvre

Avoidance manoeuvres will not be mathematically correct also for two reasons:

- in avoidance by altering the course, the ship's speed decreases relative to the helm movement. Thus the manoeuvre is carried out practically, but mathematically it is inaccurate,
- due to inaccurate plotting our results are mathematically imprecise.

2.4. CPA AND TCPA OF TWO OBSERVED TARGETS

When observing targets on the radar screen we are not interested only in their movement relative to own ship, but also their movement relative to each other. However, if we know what the distance of their passing will be, we can anticipate their possible alteration of the course or speed, which may influence our future manoeuvre.

The avoidance manoeuvre at a definite CPA should be carried out early enough. The closer to the CPA circle the APT is located the greater alteration of the course is necessary to pass the target at a definite distance. The necessary course alteration can reach up to 90°, which, however, is not supported by some ARPA or simulator software, and in such case the whole system is blocked.

From this we can draw two conclusions:

- avoidance manoeuvre for a relevant CPA must start on time,
- if the observed target approaches too close to the CPA circle, the CPA condition should be reduced.

3. EXPERIMENTAL PART

At a definite critical distance due to the limited time to the CPA the officer on watch has the last chance to realise the emergency procedure, which depends on the ship's manoeuvring characteristics and the officer's competence to carry out graphical or ARPA assisted plotting. In other words, the safe passing distance must be longer than the distance which would prevent risk of collision above all due to the uncontrolled and unexpected manoeuvres of other ships. Prudence and own ship are two elements which the officer on watch should always keep in mind. International Regulations for Preventing Collisions at Sea define all actions that should be carried out by both ships in all passing situations. Unfortunately, even a reasonable and competent officer on watch cannot be sure that the other ship is going to act reasonably, safely and in the spirit of good seamanship.

3.1. COMPUTERISED DYNAMIC SHIP'S MODEL

The computerised dynamic ship's model is a computer program which calculates the movement of each individual simulated ship in real time. It is based on the actions of navigating officers and the conditions affecting the ship. Momentary conditions, such as depth, current speed etc. can be computed from the current ship's position. They are supplied to the dynamic model together with the bridge orders (helm, main propulsion control, etc.)[1]. The dynamic model does not comprise only the hydrodynamic characteristics of the hull but also the models for the ship's navigation instruments, i. e. the main propulsion or steering gear. The main output of the dynamic model is the ship's movement, but we calculate mathematically also the value of the signal from the navigation instruments on the navigating bridge (RPM, helm position).

In developing the model of optimal avoidance manoeuvre we used a computerised dynamic model of a real bulk carrier (M/V Jargara). The results were tested also on the ship *Laho* in the Bay of Koper.

3.2. DEFINING ELEMENTS AND CONDITIONS

In the International Regulations we often come across the word *may*, which is understood as optional. The Master Judovič gives in his paper the case of the rudder angle to 70° (such angle is necessary for the ships to approach at a desired CPA), where with the help of the angle turning speed, delay in alteration of the rudder position[2], approaching speed and by adding the desired CPA, he obtained the distance at which the avoidance manoeuvre should be started at the latest [1].

For the purpose and aim of the research (simplification of procedures) we decided to substitute the following elements in the collision avoidance manoeuvre in order to preserve the desired passing distances (Table 1).

Table 1 - Substitution of avoidance manoeuvre elements

Element	Judovič, A. B.	Author
Constant	CPA	Limited Point of Approach (LPA)
Variable	Angle turning speed, delay in alteration of rudder position	Tactical Diameter (TD)
Variable	Approaching speed of ships	Degree of Collision Risk (DCR)

Impact of rudder angle or speed[4] on the tactical diameter is shown in Figure 4.

Alteration of rudder angle or speed causes different values of the tactical diameter that have to be considered in manoeuvring.

Justification of DCR alteration[5] with the approaching speed was confirmed by the simulation method (Figures 5, 6, 7 and 8).

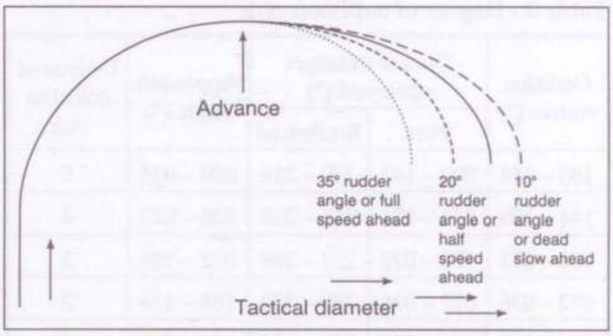

Figure 4 - Impact of rudder angle or speed

Figure 5 - Degree of collision risk at approach angle 000°

Figure 6 - Degree of collision risk at approach angle 036°

3.3. SIMULATION

Instead of seven or eight [3] we used five different situations. Thus, we reduced the incomprehensibility of some situations. Table 2 shows the values of individual elements necessary to make real collision scenarios. The table below was used as the basis for making a model of optimal avoidance manoeuvres of various collision scenarios.

Table 2 - Degree of collision risk

Collision course (°)	Course of target observed (°)		Approach angle (°)	Degree of collision risk
	Port	Starboard		
180 – 144	000 – 144	180 – 216	000 – 036	5
144 – 108	144 – 108	216 – 252	036 – 072	4
108 – 072	108 – 072	252 – 288	072 – 108	3
072 – 036	072 – 036	288 – 324	108 – 144	2
036 – 000	036 – 000	324 – 000	144 – 180	1

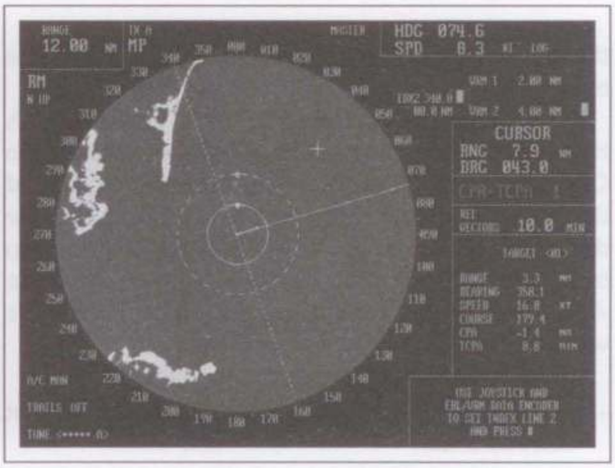

Figure 7 - Start of manoeuvre at distance 4 Nm at approach angle 000°

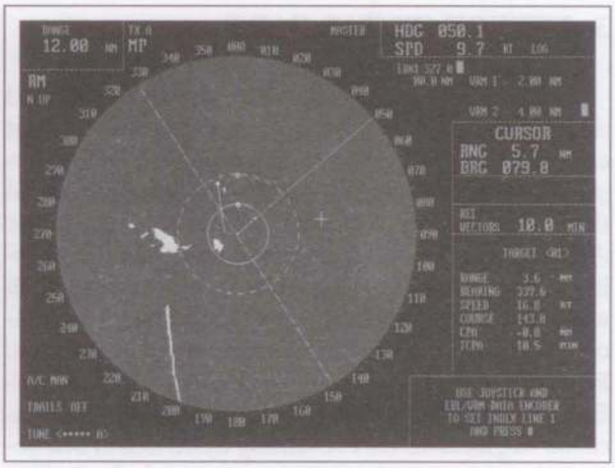

Figure 8 - Start of manoeuvre at distance 4 Nm at approach angle 324°

Numbering was made according to the degree of risk of collision considering two auxiliary hypotheses:

- wider collision angle – higher relative speed of target observed – greater risk of collision,
- narrower collision angle – higher relative speed of observed target – greater risk of collision.

Table 3 compares elements of avoidance manoeuvre. This was used to make the algorithm of optimal avoidance manoeuvre considering the desired approach distance:

LPA + TD *DCR = *LSD* *(Latest starting distance)*[6]

Further we shall try to verify the given formula by simulating manoeuvring characteristics of the computerised model of a real bulk carrier. The formula is confirmed relative to the criterion of the beam line position that must be equal to the algorithm - LPA. In our case the LPA will be 2 Nm. Due to the repetition of data, simulation will be carried out at lower limits of sectors. In case of ambiguity or limitations of the navigation instruments, such as deleting of observed target on the radar screen, we would perform the simulation in the area of the individual sector.

Table 3 - Comparison of avoidance manoeuvre elements

Element	Judovič, A. B.	Author
Turning angle speed for 70° turning (A)	1°/s * 70° (70 s = 1.1666667 min)	
Angle turning speed and delay in alteration of rudder position (B)	2 min	Tactical diameter (TD)
A + B = C	3.2 min	
Approach speed (D)	27 Nm (4.5 cables per minute) * C = 14.4 k/m (1.4 Nm)	TD * SNT
CPA (1.0 Nm)	D + CPA = 2.4 Nm	+ MOS
Distance of manoeuvre starting	D + CPA	MOS + TP * SNT

Collision avoidance manoeuvre will be carried out in accordance with Rule 8, i. e. *"be positive, made in ample time and with due regard to the observance of good seamanship"*. We shall also consider Rule 15, providing: *"... If the circumstances of the case admit, avoid crossing ahead of the other vessel"*. Considerable course alterations are more appropriate, as they are easily seen and they may directly affect the choice of the right collision avoidance strategy of the other ship. It should be taken into consideration that the changes of relative movement on the radar screen are always smaller than the actual course alterations. If circumstances permit, we should avoid maximal rudder angles during manoeuvring in real situations. Tables 4 and 5 show calculated starting points of manoeuvre at 35° and 10°.

Table 4 - Model for the carriage of bulk cargo - starting point of manoeuvring at maximal rudder angle (35°)

Degree of collision risk	Approach angle (°)	TD	Formula	Starting point of manoeuvring (Nm)
5	000	0.34	2+0.34*5	
	036/324	0.34		3.7
4	036/324	0.34	2+0.34*4	
	072/288	0.34		3.36
3	072/288	0.34	2+0.34*3	
	108/252	0.34		3.02
2	108/252	0.34	2+0.34*2	
	144/216	0.34		2.68
1	144/216	0.34	2+0.34*1	
	180	0.34		2.34

Table 5 - Model for the carriage of bulk cargo - starting point of manoeuvring at rudder angle 10°

Degree of collision risk	Approach angle (°)	TD	Formula	Starting point of manoeuvring (Nm)
5	000	0.68	2+0.68*5	
	036/324	0.68		5.4
4	036/324	0.68	2+0.68*4	
	072/288	0.68		4.72
3	072/288	0.68	2+0.68*3	
	108/252	0.68		4.04
2	108/252	0.68	2+0.68*2	
	144/216	0.68		3.36
1	144/216	0.68	2+0.68*1	
	180	0.68		2.68

3.4. RESULTS

We shall confine ourselves to the rudder angle 35° and 10°.

3.4.1. COLLISION AVOIDANCE MANOEUVRE AT RUDDER ANGLE 35°

APPROACH ANGLE 000°

The starting point of the manoeuvre is at the distance of 3.70 Nm. At own ship course alteration for 70° to starboard the observed target will be 2 Nm abeam of own ship in about 4 minutes. This course alteration however does not meet the CPA criterion of 1.3 Nm. Even with the increase in the course alteration this criterion would not change essentially. Although the target would be at a safe distance, we simulated the manoeuvre at a greater distance (4.05 Nm), which is outside the given formula. The simulation confirmed that the target would be at a safe distance at course alteration 70°. As a matter of fact, this course alteration is minimal. At course alteration 106° the approach would take place at a major distance and would also meet the CPA condition, which is 2.0 Nm.

APPROACH ANGLE 036°

The starting point of the manoeuvre is at the distance of 3.35 Nm. At own ship course alteration by 90° to starboard, the target observed will be 2.0 Nm abeam of own ship in about 3 minutes. The manoeuvre meets only our criterion, as the CPA is 1.6 Nm.

APPROACH ANGLE 072°

The starting point of the manoeuvre is at the distance of 3.00 Nm. At own ship course alteration by 110° to starboard the target observed will be 2.0 Nm abeam of own ship in about 2 minutes. The manoeuvre meets only our criterion, as the CPA is 1.8 Nm.

APPROACH ANGLE 108°

The starting point of the manoeuvre is at the distance 2.70 Nm. At own ship course alteration by 75° to port (true course 284°) the target observed will be 2.0 Nm abeam of own ship in about 16 minutes. The manoeuvre meets both criteria. Turning to port was carried out due to the said Rule 15.

APPROACH ANGLE 144°

The starting point of the manoeuvre is at the distance of 2.35 Nm. At own ship course alteration by 45° to port (true course 314°) the target observed will be 2.0 Nm abeam of own ship in about 10 minutes. The manoeuvre meets both criteria.

APPROACH ANGLE 170°

Due to radar or ARPA limitations (loss of signal) the trial was carried out in the area of this sector. The starting point of the manoeuvre is at the distance of 2.35 Nm. At own ship course alteration by 20° to port (true course 340°) the target observed will be 2.0 Nm abeam of own ship in about 20 minutes. The manoeuvre meets only our criterion, as the CPA is 1.4 Nm. However, further increase of angle would meet also the other criterion.

APPROACH ANGLE 190°

Due to the above mentioned difficulties in sector 1 starboard the trial in sector 1 port was carried out also in the area of this sector. The starting point of the manoeuvre is at the distance of 2.35 Nm. At own ship course alteration by 26° to starboard the target observed will be 2.0 Nm abeam of own ship in about 20 minutes. The manoeuvre meets only our criterion as the CPA is 1.4 Nm. However, further increase of angle would meet also the other criterion.

APPROACH ANGLE 216°

The starting point of the manoeuvre is at the distance of 2.35 Nm. At own ship course alteration by 38° to starboard the target observed will be 2.0 Nm abeam of own ship in about 16 minutes. The manoeuvre meets both criteria.

APPROACH ANGLE 252°

The starting point of the manoeuvre is at the distance of 2.65 Nm. At own ship course alteration by 79° to starboard the target observed will be 2.0 Nm abeam of own ship in about 12 minutes. The manoeuvre meets both criteria.

APPROACH ANGLE 288°

The starting point of the manoeuvre is at the distance of 3.0 Nm. At own ship course alteration by 126° to starboard the target observed will be 2.0 Nm abeam of own ship in about 16 minutes. The manoeuvre meets only our criterion, as the CPA is 1.4 Nm. However, further increase of angle would meet also the other criterion.

APPROACH ANGLE 324°

The starting point of the manoeuvre is at the distance of 3.35 Nm. At own ship course alteration by 69° to starboard the target observed will be 2 Nm abeam of own ship in about 3 minutes. But this course alteration does not meet the CPA criterion, as it is "*only*" 0.7 Nm. Even with further increase of course alteration this criterion would not change significantly (the difference is 0.5 Nm at course alteration by 179° to starboard). The manoeuvre meets both criteria only in case the manoeuvring starts at the upper limit, i. e. at the distance of 3.70 Nm.

3.4.2. COLLISION AVOIDANCE MANOEUVRE AT RUDDER ANGLE 10°

APPROACH ANGLE 000°

The starting point of the manoeuvre is at the distance of 5.40 Nm. At own ship course alteration by 53° to starboard the target observed will be 2 Nm abeam of own ship in about 8 minutes. But this course alteration does not meet the CPA criterion, as it is 1.7 Nm. However, with further increase of course alteration the manoeuvre would also meet the CPA criterion. Like with 35° rudder angle we tried to start the manoeuvring at a major distance (6.05 Nm). The manoeuvre meets both criteria at minor course alteration (46°).

APPROACH ANGLE 036°

The starting point of the manoeuvre is at the distance of 4.70 Nm. At own ship course alteration by 72° to starboard the target observed will be 2.0 Nm abeam of own ship in about 7 minutes. The manoeuvre meets both criteria.

APPROACH ANGLE 072°

The starting point of the manoeuvre is at the distance of 4.05 Nm. At own ship course alteration by 90° to starboard the target observed will be 2.0 Nm abeam of own ship in about 4 minutes. The manoeuvre meets both criteria.

APPROACH ANGLE 108°

The starting point of the manoeuvre is at the distance of 3.35 Nm. At own ship course alteration by 69° to port (true course 291°) the target observed will be 2.0 Nm abeam of own ship in about 16 minutes. The manoeuvre meets both criteria. Turning to port was carried out due to the said Rule 15.

APPROACH ANGLE 144°

The starting point of the manoeuvre is at the distance of 2.70 Nm. At own ship course alteration by 40° to port (true course 320°) the target observed will be 2.0 Nm abeam of own ship in about 10 minutes. The manoeuvre meets both criteria. Turning to port was carried out due to the said Rule 15.

APPROACH ANGLE 170°

Due to radar or ARPA limitations (loss of signal) the trial was carried out in the area of this sector The starting point of the manoeuvre is at the distance of 2.70 Nm. At own ship course alteration by 20° to port (true course 340°) the target observed will be 2.0 Nm abeam of own ship in about 25 minutes. The manoeuvre meets only our criterion, as the CPA is 1.6 Nm. However, further increase of angle would meet also the other criterion.

APPROACH ANGLE 190°

Due to the above mentioned difficulties in sector 1 starboard the trial was carried out also in sector 1 in the area of this sector. The starting point of the manoeuvre is at the distance of 2.70 Nm. At own ship course alteration by 20° to starboard the target observed will be 2.0 Nm abeam of own ship in about 25 minutes. The manoeuvre meets only our criterion, as the CPA is 1.5 Nm. However, further increase of angle would meet also the other criterion.

APPROACH ANGLE 216°

The starting point of manoeuvre is at the distance of 2.70 Nm. At own ship course alteration by 34° to starboard the target observed will be 2.0 Nm abeam of own ship in about 20 minutes. The manoeuvre meets both criteria.

APPROACH ANGLE 252°

The starting point of the manoeuvre is at the distance of 3.35 Nm. At own ship course alteration by 71° to starboard the target observed will be 2.0 Nm abeam of own ship in about 20 minutes. The manoeuvre meets both criteria.

APPROACH ANGLE 288°

The starting point of the manoeuvre is at the distance of 4.05 Nm. At own ship course alteration by 114° to starboard the target observed will be 2.0 Nm abeam of own ship in about 25 minutes. The manoeuvre meets both criteria.

APPROACH ANGLE 324°

The starting point of the manoeuvre is at the distance of 4.70 Nm. At own ship course alteration by 51° to starboard the target observed will be 2.0 Nm abeam of own ship in about 5 minutes. But this course alteration does not meet the CPA criterion, as it is only 1.2 Nm. Even with major course alteration this criterion would not change significantly (the difference is 0.4 Nm at course alteration by 166° to starboard). The manoeuvre meets both criteria only in case the manoeuvring starts at the upper limit, i. e. at the distance of 5.40 Nm.

4. CONCLUSION

Throughout the research, from the conception to the realisation we were facing problems and dilemmas. Now that the research is over, it seems that we are only at the beginning. The research reveals new findings and proposes novelties which would provide a higher degree of effectiveness in the choice of collision avoidance strategy. However, we should not expect radical decrease of collisions even with the proposed optimal model of collision avoidance manoeuvre, as the change of behaviour pattern of a navigating officer is a long-term process which requires also training of definite technical and technological conditions.

The effectiveness of the proposed model depends on the technological and human factors, particularly the interrelations between the management and support levels. The navigating officer remains thus, the key factor providing efficient execution of the proposed manoeuvre model.

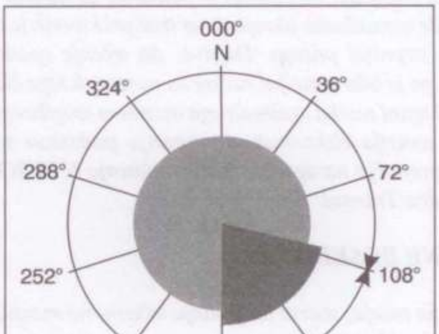

Figure 9 - Schematic demonstration of the model of optimal collision avoidance manoeuvre on the high seas

The results of the research [4] confirm the hypotheses of the optimal avoidance and generally support its application of manoeuvring at lower limits of the sector. However, the above definite sectors (5th sector, above all approach angle 180°) require the application of the model at major distances or at the upper limits of each individual sector. The very 5th sector on the portside and the approach angle 180° in some trials proved the incorrectly set algorithm of the model. The research findings have also confirmed that the collision course decisively affects the reliability of general conclusions, as it directly depends on the relative speed of the target observed and on the fact that the algorithm of the manoeuvre can be developed by dividing the radar screen into sectors.

It should be pointed out that the results of the experimental part derive above all from the said research; therefore, they can be related or transferred entirely to all the circumstances. Particularly on rough sea the safety distance should be increased by at least 0.5 Nm according to Beaufort scale. The approach is considered to be at a safe distance when ships approach far enough to avoid collision, particularly in case of a wrong manoeuvre or in some unpredicted circumstances, such as the main propulsion or steering gear failure.

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POVZETEK

Iz analize podatkov o ladijskih nesrečah je razvidno, da sta pri večini teh dogodkov prisotna poškodba trupa in trčenje ladij. Na splošno bi lahko nezgode ladij združili v dve osnovni kategoriji. Nezgode, ob katerih je potrebno za nadzor in ublažitev škode nemudoma ukrepati, ter tiste pri katerih je primeren nekoliko strpnejši pristop. Dejstvo, da trčenje spada v prvo skupino, pa je bilo temeljni razlog za nastanek tega članka.

Predlagani model optimalnega manevra izogibanja trčenja ladij na temelju elektronskega zbiranja podatkov smo oblikovali s pomočjo navigacijskega simulatorja NTPRO – 1000, proizvajalca Transas, Ruska federacija.

KLJUČNE BESEDE

Varnost na morju, sistem izogibanja trčenju na morju, začetek manevra izogibanja trčenju.

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2. "... considering the angle turning speed 1?/s and the delay in alteration of the rudder, which together takes 2 minutes, we need about 3-3.5 minutes for 70? rudder angle, which means the distance of about 1.5 Nm at the approach speed of 27 knots (4.5 cables per minute). Further, by adding the desired CPA - 1 Nm the calculation shows that the latest start of the collision avoidance manoeuvre should be at the distance 2.5 Nm"... [1] .
3. Limited point of approach is marked with the abbreviation LPA and it represents the distance at which the observed vessel is located while abeam of own vessel, either on port or starboard side. In practice the manoeuvre is believed to have been executed successfully when the ship is at the desired safe distance [2]. This is usually when the avoided ship is abeam of own ship, as at this point the returning to the original course can already start.
4. Here the angle turning speed and the delay in alteration of rudder are already considered, as the tactical diameter is the function of speed.
5. The degree of collision risk is proportional to the size of collision course.
6. Distance at which we must start manoeuvring at the latest.

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