CALCULATION OF SAFE SPEED AND
MINIMALLY ADMISSIBLE DISTANCE OF
CLOSING OF SHIPS DURING RADAR
INFORMATION USAGE

Grygorii Kalinichenko
Assistant
Department of Theory and Ship's construction
gregory_k@ukr.net

Yevgeniy Kalinichenko
PhD, Associate Professor
Department of Ship Handling
kyevgeniy@ukr.net

1National University Odessa Maritime Academy
8 Didrikshone, str., Odessa, Ukraine, 65029

Abstract: Exceeding the safe speed and the minimum allowable
distance when ships approach each other is considered as one of the main reasons for their collision, especially when using radar information when sailing in reduced visibility or in confined areas. When assigning a safe speed, among other factors, the rules recommend to take into account the state of visibility of the maneuverable capabilities of the ship, especially the distance required to completely stop the ship, as well as the characteristics, efficiency and limitation of radar equipment.

COLREGs strongly recommend the use of radar equipment to determine excessive convergence and the risk of collision of ships, subject to compliance by the navigator/operator with any restrictions imposed on the radar [2]. In addition to the qualitative recommendations in the COLREGs there are no quantitative estimates of safe speed and excessive convergence of ships. Each navigator subjectively assigns a safe speed and defines the minimum allowable approach distance of ships [3]. Because of this, in almost every case of collisions of ships, the main reasons are a significant excess of safe speed and a lowered distance of permissible approach of ships.

3. Results
The minimum allowable distance will be determined by the radius of the danger zone of approach of ships, \( R_{dz} \).

When using a radar station (radar), the radius of the danger zone of approach of ships can be determined from the following expression:

\[
R_{dz} = a + 2S_d.
\]

Where \( R_{dz} \) – radius of the danger zone; \( S_d \) – length of the stopping distance of the ship at the initial speed \( v \); \( a \) – radar parameter.

As can be seen from formulas (1) and (2), the radius of the danger zone and the magnitude of the safe speed depend on the braking characteristics of the ship and the radar parameter \( a \), which should take into account the technical capabilities of the radar to detect the danger of the echo of another ship entering the danger zone. Quantitatively, the parameter \( a \) is expressed by distance, so its value can be represented as a dependency:

\[
a = V_0T,
\]

where \( V_0 \) – relative speed of approach of the ships; \( T \) – observation time required to detect a dangerous approach of ships with the required accuracy.

The shortest distance to approach ships is determined by the formula given in [7]:

\[
d_{sh} = d \frac{\theta'}{V_0}.
\]

Where \( d_{sh} \) – the shortest approach distance; \( d \) – detection range of threatening ship; \( \theta' \) – rate of bearing change.

The error in determining the shortest approach distance of ships will occur mainly due to inaccuracies in determining the rate of bearing change, since the distances are measured using radar relatively accurately. If in the presence of the danger of collision of ships the condition \( d^2 > d_{sh}^2 \) is satisfied, then the relative speed of approach of the ships becomes close to the
radial one and can be measured on the radar screen with great accuracy. Given these circumstances, the error in the shortest distance will be equal to:

$$\delta_{\text{shortest}} = d^2 \frac{\delta \theta'}{V_0}.$$  \hspace{1cm} (5)

From where

$$V_0 = d^2 \frac{\delta \theta'}{\delta_{\text{shortest}}}.$$  \hspace{1cm} (6)

For radars operating in the centimeter wavelength range, the standard error in the rate of change of the bearing is: $60 \times 10^{-6}$ radian/s (about 0.2 degrees/min.) [3]. As a marginal error of the shortest distance, $\pm 1$ mile can be taken, then the uncertainty of the side of the divergence of the ships will be completely excluded.

After substituting these values in the formula (6), let's obtain:

$$V_0 = d^2 \left( \frac{60 \times 10^{-6} \times 3600}{1,0} \right) = 0,22d^2,$$  \hspace{1cm} (7)

where $V_0$ – relative speed in the nodes.

The error in the rate of bearing change is determined by the formula obtained in [3]:

$$\delta_{\theta'} = \delta_{\theta} \frac{12}{NT},$$

from where

$$T = \frac{\delta_{\theta}}{\delta_{\theta'}} \frac{12}{N}.$$  \hspace{1cm} (8)

where $\delta_{\theta}$ – standard error in the bearing, equal to 0.018 radian (about 1 degree); $\delta_{\theta'}$ – error in the rate of bearing change, equal to $60 \times 10^{-6}$ radians/s; $N$ – the number of marks of the echo signal during the observation time, depending on the speed of antenna rotation.

Substituting these values into formula (8), let's obtain:

$$T = \frac{0,018}{60 \times 10^{-6} \frac{12}{\sqrt{N}} \frac{1038}{\sqrt{N}}}.$$  \hspace{1cm} (9)

The rotation speed of ship radar antennas is never less than 15 rpm, so the value of $N$ can be obtained from the expression

$$N = \frac{1}{4} T.$$  \hspace{1cm} (10)

Substituting expression (10) into formula (9), let's find the minimum observation time for the given conditions:

$$T = \sqrt{4 \times 1038^2} = 163s = 0,045\text{min.}$$  \hspace{1cm} (11)

Express the parameter $a$ through the detection range of the echo signal:

$$a = V_0 \cdot T = 0,22d^2 \cdot 0,045 = 0,01d^2.$$  \hspace{1cm} (12)

Taking into account this expression, formula (1) takes the following form:

$$R_{d,z} = 0,01d^2 + 2S_z,$$  \hspace{1cm} (13)

and correspondingly,

$$S_z = \frac{1}{2} \left( R_{d,z} - 0,01d^2 \right).$$  \hspace{1cm} (14)

The effect of parameter “$a$” on the radius of the danger zone is schematically shown in Fig. 1. Due to the presence of errors in the assessment of the risk of collision, the position of the target on the radar screen can be represented as a shaded area of a circle with a radius numerically equal to the parameter $a$. Since the parameter $a$ is a function of the distance at which the definition of a collision hazard begins, as the distance decreases, the echo area will decrease. To ensure that the echo of another ship will pass from the observer’s ship at a distance of at least two stopping distances, the parameter value should be added to this distance.

Fig. 1. Influence of parameter “a” on the radius of the danger zone

4. Discussion of results

Let's consider examples of calculating the radius of the danger zone and stopping distance at a given speed for a particular ship, the calculation of the braking characteristics of which is given in [8–10].

Let's present dependencies $S = f(V)$ and $V = f(S)$, when braking the ship for full reverse, in the form of analytical expressions:

$$S = 0,07931 + 0,6263V - 0,01496V^2,$$  \hspace{1cm} (15)

$$V = 0,426 + 0,91S + 0,262S^2,$$  \hspace{1cm} (16)

where $S$ – in cable; $V$ – in knots.

Example 1. The ship follows the open sea, far from the coast, in conditions of reduced visibility. The displacement of the ship is 22100 tons, the speed is 14 knots (full maneuverable advance).

According to the formula (15), let's calculate the stopping distance when the thruster is reversed for full reverse:

$$S = 0,07931 + 0,6263 \times 14 - 0,01496 \times 196 = 5,9\text{ miles.}$$

Radar detection range of ships is 7 miles. Counting the radius of the danger zone:

$$R_{d,z} = 0,01 \times 7^2 + 2 \times 5,9 = 1,67\text{ miles.}$$

Example 2. The ship should be in narrowness with reduced visibility. The range of divergence from ships is limited to
0.9 miles, and the target detection range is limited to a five-mile radar scale. Based on these conditions, it is required to determine the safe speed.

According to the formula (2) let's find the stopping distance:

\[ S_v = \frac{1}{2} (0.9 - 0.01 \cdot 5^2) = 0.32 \text{ miles} = 3.2 \text{ cables.} \]

At \( S_v = 3.2 \) cables, the safe speed will be equal to:

\[ V = 0.426 + 0.9101 \times 3.2 + 0.262 \times 10.24 = 6.0 \text{ knots.} \]

If, however, for any reason, the observer's ship cannot prevent excessive approach to another ship or if it hears a sound foggy signal ahead of its beam, then, according to Rule 19 of the COLREGs, it should reduce the stroke to the minimum until it passes collision hazard.

As a result of research, an analytical relationship is obtained between the safe speed and the minimum allowable approach distance of ships when using radar information. The developed method allows to automate the choice of safe speed and eliminate the subjective factor when it is appointed by navigator.

References