ISOLINE OF THE BORDER OF NAVIGATION SAFETY ZONE OF A VESSEL

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ABSTRACT

Prevention of the majority of emergency situations in navigation is based on observing a certain distance between vessels, which allows timely taking precautionary measures in order to avoid contact. The thus created conditional space of safety distances forms a navigation safety zone. The article gives a universal conceptual definition of such a zone, a generalized structural classification of factors affecting its size and shape, the nature of the isolinear zonal boundary. The concepts of isoasphalia as an idealized safe boundary, as well as an isoasphalic surface forming an idealized safe area around the vessel are introduced. On the basis of set theory, a variational law of variation of piecewise functions describing a safe space asymmetric with respect to the vessel's diametric plane is derived. The resulting expression allows us to identify the boundary of an asymmetric elliptical navigation safety zone.

Keywords: *sea vessels, navigation safety, idealized model, isoline boundary, isoashpalia, isoasphalic surface, asymmetric elliptic zone, set theory, variational law.*

Background. *When solving the main complex of tasks related to ensuring safety of navigation, a vessel always maintains the required distance between other mobile and stationary objects. This distance is necessary for maintaining a given level of navigation safety, as well as obtaining time for response actions at a critical time. The set of points of space corresponding to insurance distances at all course angles forms around the vessel a zone of a certain shape and size, called, according to [3], a «navigation safety zone (NSZ)». Some authors during the conceptual development of the notion of the NSZ offered various interpretations of the term [1–5, 8–14].*

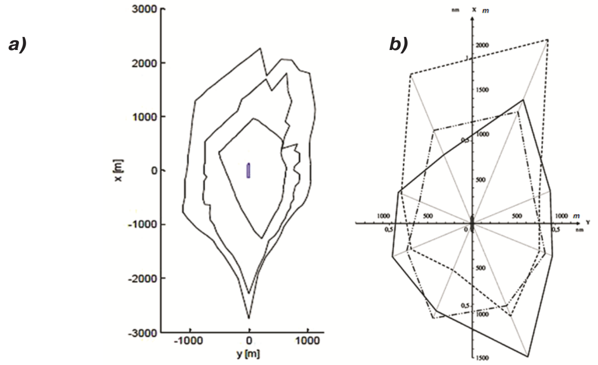
Objective. *The objective of the author is to consider issues related to the isoline of the border of navigation safety zone of a vessel.*

Methods. *The author uses general scientific and engineering methods, set theory, variation law, modeling, comparative analysis, and mathematical apparatus.*

Table 1

Factors affecting the size and shape of the navigation safety zone

No.	Factors	Evaluation criteria
1	Navigational	• technical means and methods of navigation; • relationship with another isoline; • area and mode of navigation; • features of navigation in high risk areas (High Risk Area); • navigation operations performed by the vessel's crew (anchoring, mooring, ship-to-ship operations, helicopter operations); • pilotage; • depth; • air space; • number and location of other objects.
2	Hydrometeorological	• wind; • sea motions, waves; • current; • tidal phenomena; • density of the marine environment; • storm conditions; • ice conditions; • state of visibility.
3	Regulatory	• COLREGS-1972 (IRPCS) • port VTS; • requirements of international conventions and circulars; • guidance documents of states concerning the safety of navigation; • requirements of the safety management system (SMS); • the captain's instructions for carrying watch.
4	Static	• parameters of the vessel and other targets; • constant forces and moments of force (weight of the vessel, support forces).
5	Kinematic	• vessels' heading; • speed, acceleration and deceleration of the vessel; • relative speed of approach.
6	Dynamic	• maneuvering and inertial characteristics of the vessel; • driving, external and temporary – variables – forces and moments of forces acting on the vessel during operation.
7	Psychological	• boatmaster's practical experience; • degree of generality and objectivity of assessment of the existing navigational situation; • communication relationship with other vessels and facilities; • organization of the work of the bridge.



Pic. 1. NSZ of a complex shape.

Results. *Our concept of isolinearity is closer to the variant that describes the boundary as applied to any method of NSZ.*

The navigation safety zone is the space around the vessel formed by a systematized set of distance points at all course angles, with the risk boundary representing the curve of equal values (isoline) of the safety level of the vessel's navigation when it comes into contact with any objects.

The resultant influence on dimension and configuration of such space is provided by a set of factors and criteria, identified on the basis of many years of research [1–5, 8–14], their quantification, which can be supplemented by an analysis of practical skills obtained in the process of real operation of vessels. Their generalized structural classification is presented in Table 1.

Obviously, with the combined consideration of all factors, the boundary of the navigation safety zone will be transformed into an extremely complex figure, and, accordingly, a complex mathematical description. This is due to the following main aspects:

- *navigational, hydrometeorological, regulatory and static factors are causal, are observable and cause the impact of the causal dynamic impacts on the vessel, as well as the degree to which the kinematic factors change to maintain a given level of safety, depending on the existing navigational situation;*
- *variable forces and moments that are the criteria for estimating dynamic external influences are unobservable and can be detected by excluding from the magnitude of the resulting effect of analytically formulated known components;*
- *causal hydrometeorological and, as a consequence, dynamic effects on the vessel can take a regular or irregular character, while exhibiting stochastic and intermittent properties;*
- *a significant part of the factors quoted is unmanageable (with the exception of the course and speed of the vessel, while the steadiness of the vessel on the course, the turning ability under the given conditions of navigation, the traffic density of ships with an adequate control system (VTS) [1] can be implicitly controlled);*
- *psychological factors are the criteria for cumulative assessment of the cause and effect impacts on the vessel during its operation in the presence of the boatmaster, however, due to his psychophysical and emotional state, the degree of vessel safety in the prevailing situation cannot always be objectively determined;*
- *criteria for assessing psychological and regulatory factors do not have sufficient clear and objective regulation, taking a recommendatory or variable character;*
- *distribution of the acting forces and moments along the length of the hull is uneven.*

The above aspects were used in the simulation of NSZ of large-tonnage vessels following a limited navigation area (Pic.1a) [12] and probabilistic areas recommended to tankers depending on the prevailing situation (Pic. 1b) [13].

The boundaries of models proposed in Pic. 1 demonstrate figures, which are quite laborious in the mathematical description. For probabilistic domains, there is a variety of formalization variations with regularly occurring new situations, complicating assessment of the situation, and increasing decision-making time.

Thus, the maximal correlation of the configuration of NSZ with the topological criterion which is the simplicity of the mathematical description and the geometrical representation of the boundary, is the fundamental condition, the compliance with which will allow most effectively to solve the problems of securing navigation [3].

Hence one more fundamental definition:

A formalized model of the navigation safety zone can be such a theoretical model, the form and parameters of which allow one to take into account as much as possible the known influencing factors, being consistent with the topological criterion.

Presently, the variety of forms and parameters of NSZ models is explained by the peculiarities in the approaches, methods, the degree of objectivity of researchers in systematizing, evaluating and recording factors that affect the configuration of the safety zone. However, all these approaches are generalized by the tendency to identify and model the formalized boundary of the safe space around the vessel.

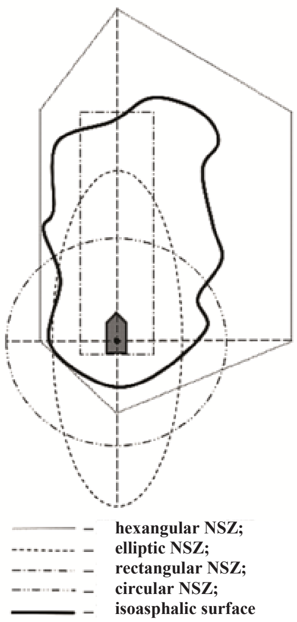
It is offered to give to the formalized boundary of NSZ a generalized abstract definition of «isoasphalia»:

Isoasphalia (from Greek ισος – equal, ασφάλεια – safety) – a curve that forms the boundary of the navigation safety zone and represents a line of equal values of the degree of safety.

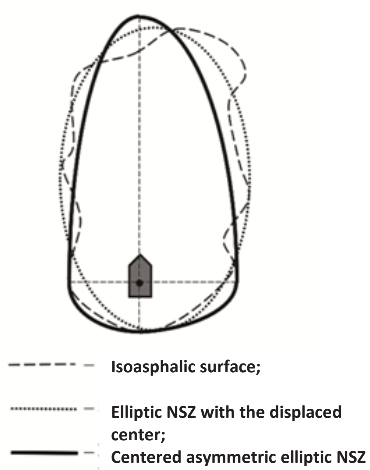
The natural derivative of this definition:

Isoasphalic surface – region limited by isosphalia (Pic. 2).

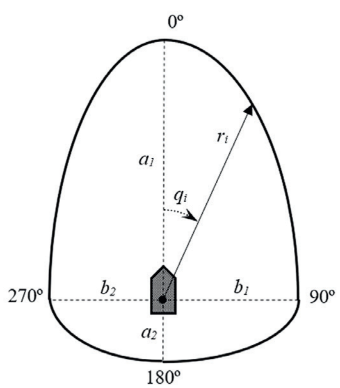
The paper [3] proposes the formation of an elliptic NSZ, which best generalizes all other forms of safe space around the vessel, with the law of center displacement depending on the kinematic characteristics, maneuverability of the vessel, situations and conditions of navigation with the aim of formalizing its boundary (Pic. 3). However, modeling a non-centered navigation safety zone can make it difficult to assess the situation and cause additional complexity in identifying the



Pic. 2. Conceptual imaging of an abstract isoasphalic surface.



Pic. 3. Variations of idealized NSZ surfaces.



Pic. 4. Model of asymmetric elliptic NSZ.

vessel's displacement relative to the center of the safe space.

In this case, a variant of the asymmetric centered elliptic NSZ is used to generalize and universalize the models of interest to us. The formalization of its model is assumed by approximating the laws of adaptation of the border to the «vessel-model of NSZ» system when the vessel is in the center of the isoasphalic surface.

To identify its boundary, based on systematization of the set of elements, which include points of safe distances at all course angles, it is advisable to use the function

$$\begin{cases} P_{NSZ} = \{p_{r_0}, p_{r_1}, \ldots, p_{r_i}, p_{r_{i+1}}, \ldots, p_{r_n}\}; \quad n \to \infty; \\ r_i = r(q_i); \quad i \in [0; n], \end{cases} \qquad (1)$$

where P_{NSZ} is an infinite limited set of points of safe distances forming the boundary of NSZ; r_i – i-th distance from the control center of the vessel to the point belonging to NSZ boundary, m; p_{ri} – point on the boundary of NSZ, corresponding to the i-th distance; q_i – heading angle of the i-th distance, degrees; n – number of elements of NSZ system.

Obviously, in general, the i-th distance of an elliptic NSZ, symmetric with respect to the principal axes, is its radius vector, determined from the expression [7] on the corresponding heading angle:

$$r(q_i) = \frac{ab}{\sqrt{a^2 \sin^2 q_i + b^2 \cos^2 q_i}}, \qquad (2)$$

where a, b are large and small semiaxes of the ellipse of NSZ, m.

To identify the boundary of an asymmetric elliptic NSZ, we modify function (2) by estimating the boundary of the safe space around the vessel from the point of view of set theory [6]. Pic. 4 shows that the function for describing an infinite bounded set of points of safe distances P_{NSZ} is given piecewise: by various combinations of the function (2) on certain sector intervals bounded by longitudinal and traverse semiaxes:

$$r(q_i) = \begin{cases} \dfrac{a_1 b_1}{\sqrt{a_1^2 \sin^2 q_i + b_1^2 \cos^2 q_i}}; & q_i \in [0^\circ; 90^\circ) \\ \dfrac{a_2 b_1}{\sqrt{a_2^2 \sin^2 q_i + b_1^2 \cos^2 q_i}}; & q_i \in [90^\circ; 180^\circ) \\ \dfrac{a_2 b_2}{\sqrt{a_2^2 \sin^2 q_i + b_2^2 \cos^2 q_i}}; & q_i \in [180^\circ; 270^\circ) \\ \dfrac{a_1 b_2}{\sqrt{a_1^2 \sin^2 q_i + b_2^2 \cos^2 q_i}}; & q_i \in [270^\circ; 360^\circ), \end{cases} \qquad (3)$$

where $a_{1,2}$, $b_{1,2}$ are variations of longitudinal and traverse semiaxes with the asymmetry of NSZ ellipse, m.

Correlating the elements of the semiaxes of the elliptic NSZ, the boundary of which is described by the function (2), with the analogous elements of the piecewise functions (3), we determine the sectoral intervals of the variational influence of the elements a_1, a_2, b_1, b_2 on the formalization of the zone boundary:

$$a = \begin{cases} a_1; & q_i \in [270^\circ; 360^\circ) \cup [0^\circ; 90^\circ) \\ a_2; & q_i \in [90^\circ; 270^\circ) \end{cases}$$

$$b = \begin{cases} b_1; & q_i \in [0^\circ; 180^\circ) \\ b_2; & q_i \in [180^\circ; 360^\circ). \end{cases} \qquad (4)$$

The use of a piecewise constant function allows us, through the analysis of expressions (2)–(4), to

$$r(q_i)=\frac{\left[a_1(1+\Delta a)+a_2(1-\Delta a)\right]\cdot\left[b_1(1+\Delta b)+b_2(1-\Delta b)\right]}{2\sqrt{\left[a_1(1+\Delta a)\sin q_i+a_2(1-\Delta a)\sin q_i\right]^2+\left[b_1(1+\Delta b)\cos q_i+b_2(1-\Delta b)\cos q_i\right]^2}}. \qquad (6)$$

formulate a variational law for determining the parameters of the semi-axes of an asymmetric elliptic NSZ:

$$a=\frac{a_1(1+\Delta a)+a_2(1-\Delta a)}{2}$$
$$\Delta a=\begin{cases}1, & q_i\in\left[270^\circ;360^\circ\right)\cup\left[0^\circ;90^\circ\right)\\ -1, & q_i\in\left[90^\circ;270^\circ\right)\end{cases}$$
$$b=\frac{b_1(1+\Delta b)+b_2(1-\Delta b)}{2} \qquad (5)$$
$$\Delta b=\begin{cases}1, & q_i\in\left[0^\circ;180^\circ\right)\\ -1, & q_i\in\left[180^\circ;360^\circ\right),\end{cases}$$

where Δa, Δb are variational coefficients.

As a result, we derive a piecewise-continuous function that allows us to describe the boundary of an asymmetric elliptic NSZ, a particular variant of which is the function (2) (6).

The obtained analytical expression (6) helps to realize the method of identifying the boundary of an asymmetric elliptic NSZ by using longitudinal and traverse semiaxes of an ellipse that are not equivalent to one another.

Conclusions. *The approach proposed in the article allows us to generalize the methods of formalized representation of NSZ boundary [3]. Since along with the rational distribution of safe space around the vessel [1], it becomes possible to interpret the configurations of a symmetric elliptic or circular navigation safety zone. Despite the asymmetric properties, the vessel is located in the center of the isoasphalic surface. Accordingly, it is not necessary to take into account its displacement relative to the center of NSZ, and all non-centered or sector variants [9, 11] can be specified using the expression (6) «border adaptation techniques» by incrementing the model parameters. To identify the parameters of longitudinal and traverse semiaxes in relation to large-capacity vessels, based on tabulated data on displacement, the technique proposed in [4] can be applied.*

Thus, based on the results of the work done, we will outline the goals and directions for further research:

• formalization of the factors influencing the size and shape of the navigation safety zone (see Table 1) with a view to mathematically adapting them to the «vessel–NSZ» system;

• identification of methods for identifying longitudinal and traverse semiaxes parameters, as well as radii for individual sections of an asymmetric elliptic NSZ;

• complex modeling of asymmetric elliptic NSZ;

• adaptation of the boundary of safe distances to the composite system of the existing situation, taking into account the influence of the limiting number of factors and the criteria for their evaluation on the parameters and final configuration of NSZ, which will satisfy its definition as an isoasphalic surface as much as possible.

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