Strategy of Ship Control Under Intensive Icing Conditions

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ABSTRACT

The problem of making decisions on ship control under conditions of intensive icing has been discussed. A mathematical model of icing dynamics and criterion basis which provides ship's safety in this critical situation have been developed. The problem of making decisions on controlling ship stability in fuzzy environment has been set. Mathematical simulation of dynamics of ship's interaction with the environment in conditions changes in ice load and stability characteristics has been performed. Analyzing the results of the simulation has enabled to estimate risks under the considered conditions.

Keywords: *dynamic of ship, intensive icing, fuzzy environment, mathematical simulation*

1. INTRODUCTION

Risk estimation is one of complicated procedures in decision-making problems [Bogdanov, Degtyarev, Nechaev, 2001], [Nechaev, 2002]. Presently different approaches to risk estimation are used. The approach based on the probability theory and the catastrophe theory within the systems with a final set of discrete states is most popular. It involves application of theory and methods for analyzing risk situations scenarios. Investigation of very small probability risk scenarios, which are characterized by great damages, is the mostly developed approach in solving the problems of safe seafaring. Among the methods for judging risks in providing stability of ships the approach suggested in [Belenky, Sevastyanov, 2003], [Kobylinski, Kastner, 2003], [Kobylinski, 2003], [Ryrfeldt, 2003] should be singled out. Within the framework of this approach a set of operating situations is reduced to an ultimate set of estimated situations. The vector of estimated situations, where each element is a set of both ship parameters and environment parameters, is found. The characteristic polynomial is designated by the level of methods applied for investigated estimated situations. It is common practice in the problems dealing with safety of seafaring to consider only extreme situations applying fairly simple approximations of spectral density of waves. It is only recently that lengths of stormy and good weather waves are taken into account for estimation of risks characteristics storms. Information on weather characteristics, in particular on alternating storms with favorable weather, as well as complicated spectral composition of waves have been realized first in the paper [Boukhanovsky at all, 2000]. The concept of climate spectrum enabled the authors to get new data of some situations which a ship can encounter in a particular voyage. The present paper contains an analysis of an extreme situation caused by dramatic decrease in stability under conditions of intensive icing on the basis of methods and models [Nechaev, 1989], [Nechaev, Makov, 2002]. Risk estimation in this situation is performed with application of a radically new (from the point of view of estimating stability) approach dealing with making decisions in fuzzy conditions [Bellman, Zadeh, 1976]. According to the authors, this approach is mostly justified in analyzing alternatives and in selecting preferable solutions in fuzzy conditions, i.e. when information about ship's dynamics and its environment under operating conditions is limited.

2. MAKING DECISIONS IN FUZZY ENVIRONMENT

Decision making in conditions of risk can be stated as follows: there is a set of variants of solving problems (alternatives). Realization of each alternative brings to solutions. Alternatives are characterized by analyzing and estimating outcomes by indexes of efficiency. On the basis of simulating, a model of selecting alternatives enabling to solve the problem is to be built.

Formal statement of the problem is as follows. Let us assume that there is some fuzzy information characterizing a area of making decisions. This information can be presented as a cortege [Nechaev, 2002]]:

$$\langle A, E, S, T\rangle, \tag{1}$$

where A – a set of alternatives, E – area of decision making task, S – decision support system of a decision maker (DM), T – action on the alternative set A.

In the course of analyzing the set A in the environment E it is required to find the most preferable alternative which satisfies limitations C and is a way of achieving the aim G.

Solution of the problem (1) is found as a certain (specified) subset Ω of a set of alternatives A:

$$\Omega \subset 2^A \times K^A, \tag{2}$$

where 2^A – a set of all subsets of alternatives; K^A – a set of all corteges from 2 to $|A|$ in length.

Decision rule is expressed by intersection of fuzzy aims G_i and limitations C_j:

$$\Omega = \mathrm{G_1} \cap \dots \cap \mathrm{G_i} \cap \mathrm{C_1} \cap \dots \cap \mathrm{C_j} \dots \tag{3}$$

or with allowance made for their relative importance:

$$\Omega = \textstyle\sum_i k_I G_i + \sum_j k_j^* C_j; \quad \sum_i k_i + \sum_j k_j^* = 1, \tag{4}$$

where k, k^*– great importance coefficient.

Modification of decision rule (3) with regard to comparing fuzzy aims by importance will look like:

$$\Omega = G_1^{k1} \cap G_2^{k2} \cap \dots \cap G_i^{ki} \cap \dots; \quad \Omega = G_1/k_1 \cap G_2/k_2 \cap \dots \cap G_i/k_i \cap \dots \tag{5}$$

Let us specify the statement of the problem (1),(2) as applicable to analyzing alternatives when selecting a safe ship course and velocity on the basis of Bellman-Zadeh approach [Bellman, Zadeh, 1976]. We assume that X – is a universal set of alternatives. We will consider mapping φ: $X \rightarrow Y$. The elements of Y set are values of the mapping. This mapping is understood as reaction of the system on input fluctuations $x \in X$ or as some estimations of selection of corresponding alternatives. The fuzzy aim G is pre-assigned as a fuzzy sub-set of reactions Y, i.e. as a membership function μ_G: $Y \rightarrow [0,1]$.

The problem is solved to achieve the aim with specified fuzzy limitations. Let a certain alternative x enables achieving the aim with the power $\mu_G(x)$ and complies limitations with the power $\mu_C(x)$.

Then the degree of membership alternative x equals the minimum of these numbers with a membership function:

$$\mu_G(x) = \min\{\mu_G(x), \mu_C(x)\}. \tag{6}$$

With several aims and limitations the fuzzy decision is:

$$\mu_G(x) = \min \{\mu_{G1}(x), \ldots, \mu_{Gn}(x), \mu_{C1}(x), \ldots, \mu_{Cn}(x)\}. \tag{7}$$

With regard to importance of aims k_i and limitations k^*_j the result of solution is presented as

$$\mu_G(x) = \min \{k_1\mu_{G1}(x), \ldots, k_n\mu_{Gn}(x), k_1^*\mu_{C1}(x), \ldots, k_n^*\mu_{Cn}(x)\}. \tag{8}$$

Thus solution can be approached as a fuzzily formulated rule. Complying with the rule enables reaching of a fuzzily set aim. Choice of an alternative with a maximum degree of fuzzy decision membership (maximizing solution) is dictated by the condition:

$$\max_{x\in X} \mu_\Omega(x) = \max_{x\in X} \min\{\mu_G(x), \mu_C(x)\}. \tag{9}$$

3. MATHEMATICAL MODEL

The mathematical model is built on the basis of handling data of full scale observations. Allowances are made for basic data of real load condition and stability of the ship at the moment of estimation and the forecast of development of the situation in intensive icing. The condition of the ship at the initial moment is specified by the displacement, the centre of gravity coordinates *(Mo, Xgo, Ygo, Zgo)* as well as by stability indexes. The principal dimensions of the ship, the hydrostatic curves,

the centre of effort (of sails) elevation of the centre of effort of sails, free board height (including bulwark) on the fore perpendicular as well as the ship's speed on calm water have been used in the course of calculations.

While the mathematical model was being developed the authors hold the traditional ship orientation as related to wind and oncoming sea. Fig. 1 shows a triangle which represents speeds and course angle. The compass bearing wave track is CB_{WT} and the wave height is $h_{3\%}$. Steady wind is characterized by the course bearing of true wind CB_{TW} and the speed U_{TW}. The conditions, icing is developing under, feature air temperature *ta* and water temperature *tw*. If the system is used aboard a ship the aforementioned characteristics are the results of measurements, in other cases they are the results of analyzing wind and seas occurrences in the specified area of navigation.

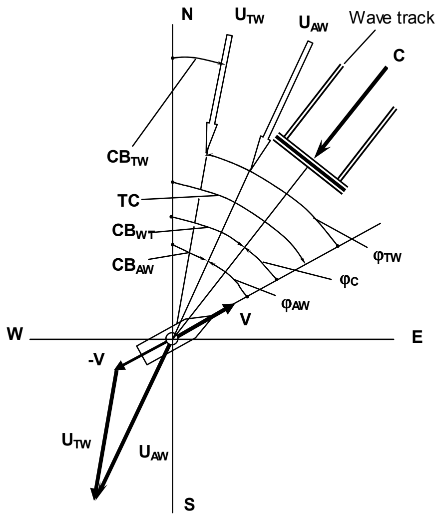

Fig.1 The triangle of speeds and course angles: V – speed of the ship, TC – true ship course, CB_{WT} – compass bearing of the wave track, CB_{AW} – compass bearing of apparent wind, CB_{TW} – compass bearing of true wind, U_{AW} – velocity of apparent wind, U_{TW} – velocity of true wind, φ_C – course angle of the ship relative to waves, φ_{TW} – course angle of true wind, φ_{AW} – course angle of apparent wind.

3.1. Rate of Ice Growing

The model of icing process depending on the course angle takes account of growing of ice in three points: 1 – on the fore perpendicular on the upper deck level, 2 – on the upper deck amid ship close aboard and 3 – on the upper deck on the after perpendicular.

The rate of ice growing in t/hr can be presented by

$$\begin{bmatrix} V_{m1} \\ V_{m2} \\ V_{m3} \end{bmatrix} = \begin{bmatrix} A_1 \\ A_2 \\ A_3 \end{bmatrix} \cdot \begin{bmatrix} \Sigma_{NAV1} \\ \Sigma_{NAV2} \\ \Sigma_{NAV3} \end{bmatrix} \tag{10}$$

where

$$\begin{bmatrix} A_1 \\ A_2 \\ A_3 \end{bmatrix} = \begin{bmatrix} F_1(\varphi_{AW}) \\ F_2(\varphi_{AW}) \\ F_3(\varphi_{AW}) \end{bmatrix} \cdot F \begin{bmatrix} h_{3\%}(h_{3\%}(0),t), f_1 \\ h_{3\%}(h_{3\%}(0),t), f_2 \\ h_{3\%}(h_{3\%}(0),t), f_3 \end{bmatrix} \cdot F(L)$$

Here $F_i(\varphi_{AW})$ are functions where influence of angle between apparent wind and longitudinal plane are taken into account:

$$F_1(\varphi_{AW}) = d_1 + d_1 \cdot Cos(d_{11}\varphi_{AW}) + kd_1 \cdot Cos(d_{12}\varphi_{AW})$$
$$F_2(\varphi_{AW}) = d_2 + d_2 \cdot Cos(d_{21}\varphi_{AW} - \pi)$$
$$F_3(\varphi_{AW}) = d_3 + d_3 \cdot Cos(d_{31}\varphi_{AW}).$$

The general view of the function $F_i(\varphi_{AW})$ is shown in Fig. 2.

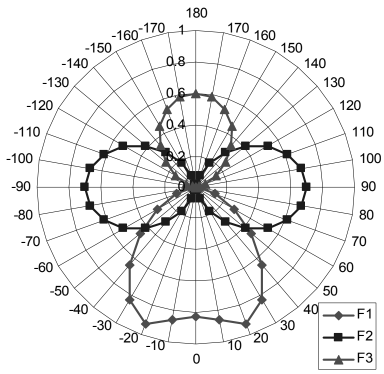

Fig.2. Functions F_1, F_2, F_3

F are functions where influence of wave height (which can be changed with time), freeboard height at points 1, 2 or 3 and ships length are taken into account:

$$F \begin{bmatrix} h_{3\%}(h_{3\%}(0),t), f_1 \\ h_{3\%}(h_{3\%}(0),t), f_2 \\ h_{3\%}(h_{3\%}(0),t), f_3 \end{bmatrix} = 1 + \frac{0.1 h_{3\%}(h_{3\%}(0),t) + 0.1}{0.1 \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} + 0.2},$$

$$F(L) = \left(1 + \frac{L-35}{93}\right)^3$$

The height of the design wave $h_{3\%}(0)$ at the moment of taking decision by the master was calculated as a function of the ship length from the formula

$$h_{3\%}(0) = 0.05\left(1 + \frac{160 - L}{135}\right)L \qquad (11)$$

but it may be prescribed arbitrarily.

If the storm strengthens, the increase in wave height is found from the formulae (Fid.3)

$h_{3\%} = h_{3\%}(0) + 0{,}07t$, m (t – hour)

Σ_{NAV} are functions where influence of water and air temperatures, apparent wind velocity, sail area and ship's velocity with regard for its decreasing on rough seas are taken into account:

$$\begin{bmatrix} \Sigma_{NAV1} \\ \Sigma_{NAV2} \\ \Sigma_{NAV3} \end{bmatrix} = \begin{bmatrix} b_{11} \\ b_{21} \\ b_{31} \end{bmatrix} N^* + \begin{bmatrix} b_{12} \\ b_{22} \\ b_{32} \end{bmatrix} N^* A_v^* + \begin{bmatrix} b_{13} \\ b_{23} \\ b_{33} \end{bmatrix} V_S^*$$

$N^* = U_{AW}(|ta|+|tw|)$; $A^* = Av/225$;
$V_S^* = (Vs/Vs_{CW}) - 0{,}5$.

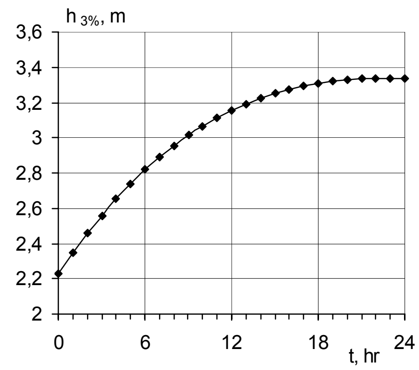

Fig. 3 Increasing of wave height shows the process of storm development

In the aforementioned formulae the following symbols are used: U_{AW} – velocity of apparent wind; ta and tw – air and water temperatures; Av – sail area; L – ship length; f_{123} – heights of freeboard on the fore perpendicular, amidships on the longitudinal centre plane and on the after perpendicular; Vs – ship velocity with regard to wind and waves; Vs_{CW} – ship velocity on calm water; a_i, b_{ij}, d_i, d_{ij} – coefficients which values are assigned in the course of statistical handling of full scale measurements.

Ice mass grooving within δt hr interval is found from the formulas:

$$\begin{bmatrix} m_1 \\ m_2 \\ m_3 \end{bmatrix} = \begin{bmatrix} V_{m1} \\ V_{m2} \\ V_{m3} \end{bmatrix} \delta t \quad , t.$$
$$m = m_1 + m_2 + m_3.$$

The rate of ice growing (in t/hr) depends greatly on course angle and direction of wind and wave vectors.

3.2. The Rate of Changing Coordinates of the Centre of Growing Ice Masses

The rate of changing the coordinates of the center of growing ice masses (in m/hr) is found by the formula:

$$\begin{bmatrix} V_{Xm1} \\ V_{Xm2} \\ V_{Xm3} \end{bmatrix} = \begin{bmatrix} A_1 L_1^* c_{x1} m^* \\ 0 \\ A_3 L_3^* c_{x3} m^* \end{bmatrix}, \quad \begin{bmatrix} V_{Ym1} \\ V_{Ym2} \\ V_{Ym3} \end{bmatrix} = \begin{bmatrix} 0 \\ A_2 B^* c_{y2} m^* \\ 0 \end{bmatrix},$$
$$\begin{bmatrix} V_{Zm1} \\ V_{Zm2} \\ V_{Zm3} \end{bmatrix} = \begin{bmatrix} A_1 H_1^* c_{z1} m^* \\ A_2 H_2^* c_{z2} m^* \\ A_3 H_3^* c_{z3} m^* \end{bmatrix}, \quad m^* = \frac{m}{M_0}. \qquad (12)$$

Here c – coefficients, which values were found (assigned) in the course of handling the results of full scale measurements.
The coordinates of ice masses center are found by the formulae:

$$\begin{bmatrix} X_{m1} \\ X_{m2} \\ X_{m3} \end{bmatrix} = \frac{L}{2} - \begin{bmatrix} V_{Xm1} \\ 0 \\ V_{Xm3} \end{bmatrix} \delta t, \quad \begin{bmatrix} Y_{m1} \\ Y_{m2} \\ Y_{m3} \end{bmatrix} = \frac{B}{2} - \begin{bmatrix} 0 \\ V_{Ym2} \\ 0 \end{bmatrix} \delta t,$$
$$\begin{bmatrix} Z_{m1} \\ Z_{m2} \\ Z_{m3} \end{bmatrix} = \begin{bmatrix} H_1 \\ H_2 \\ H_3 \end{bmatrix} + \begin{bmatrix} V_{Zm1} \\ V_{Zm2} \\ V_{Zm3} \end{bmatrix} \delta t, \qquad (13)$$

$$\begin{bmatrix} L_1^* \\ B^* \\ L_3^* \end{bmatrix} = \begin{bmatrix} 0.96 + f_1 / L \\ 0.80 + f_2 / B \\ 0.96 + f_3 / L \end{bmatrix}, \quad \begin{bmatrix} H_1^* \\ H_2^* \\ H_3^* \end{bmatrix} = 0.60 + \begin{bmatrix} f_1 / H_1 \\ f_2 / H_2 \\ f_3 / H_3 \end{bmatrix}. \qquad (14)$$

Here H_1, H_2, H_3 – the height of freeboard depth afore, amidships and astern.
General coordinates of the centre office masses are found from the equations:

$$X_m = \frac{m_1 X_{m1} + m_3 X_{m3}}{m},$$
$$Y_m = \frac{m_2 Y_{m2}}{m}, \qquad (15)$$
$$Z_m = \frac{m_1 Z_{m1} + m_2 Z_{m2} + m_3 Z_{m3}}{},$$

And the coordinates of the centre of the ship masses are found from the equations:

$$M = M_0 + m,$$
$$Xg = \frac{M_0 Xg_0 + mX_m}{M},$$
$$Yg = \frac{M_0 Yg_0 + mY_m}{M}, \qquad (16)$$
$$Zg = \frac{M_0 Zg_0 + mZ_m}{M}$$

The calculations are made at every stage at a specified interval δt hour.

3.3. Additional Resistance Due to Wind and Rough Seas and Decrease in Velocity

Resistance of ship in rough seas is calculated from the formula [Nechaev, Makov, 2002]:

$$R = \kappa_{m\psi} R_{cw} + \kappa_\varphi R_{aw0} + R_a, \qquad (17)$$

where R_{cw} – resistance on calm water at the moment of taking decision, $\kappa_{m\psi}$ - coefficient where allowances are made for influence of changes in displacement of the ship (due to ice growing) and changes in angle of trim

$$\kappa_{m\psi} = \kappa_m \kappa_\psi,$$

where

$$\kappa_m = 1 + 0.52\, m^* + 0.63\, m^{*\,2} - 0.89\, m^{*\,3},$$
$$\kappa_\psi = 1 + 0.013\,\psi + 0.007\,\psi^2.$$

Increase in resistance in irregular seas is found from

$$R_{aw} = \kappa_\varphi\, R_{aw0.}$$

Here R_{aw0} – is resistance in head irregular sea

$$R_{aw0} = 2{,}48\ L^{4{,}8} B^{2}\, h_{3\%}^{-3{,}8}\, Fr^{3{,}16} \times \times \exp(-3{,}5Fr - 3{,}23\ Fr^{0{,}143}\,(L/h_{3\%})^{0{,}5}). \quad (18)$$

In coefficient κ_φ account in taken of the course angle influence

$$\kappa_\varphi = F(\varphi, \kappa_R, \alpha).$$
$$\kappa_R = (1.2 - 0.1\sqrt{\alpha}) - (2.9\sqrt{\alpha} - 1.9)Fr,$$

Here α – waterline fullness coefficient and «a» parameter is found from the formula:

$$a = q_b \frac{10 h_{3\%}}{L}.$$

q_b – coefficient depends on the rate of developing rough seas (0.75).

Additional resistance due to wind is calculated as follows:

$$R_a = C_x \frac{\rho_a U_{AW}^{\;2}}{2} A_F$$

Here: ρ_a – air density; A_F – projection of the sail area on midship section plane; $C_x(\varphi_{AW})$ – coefficient of resistance, taken as resulted from flowing of air towards above water part of ship model in a tunnel or taken as approximated estimates; U_{AW} – apparent wind velocity. Apparent wind velocity is calculated from the formula:

$$U_{AW} = \sqrt{U_{TW}^{\;2} + Vs^2 - 2U_{TW} Vs \cdot Cos(\varphi_{TW})} \quad (19)$$

True wind velocity (m/sec) is found from the formula:

when $h_{3\%} > 1$ m $U_{TW} = 6{,}7 + 2{,}13(h_{3\%} - 1)$;

$h_{3\%} < 1$ m $U_{TW} = 16{,}7 h_{3\%}^{\;2} - 10 h_{3\%}^{\;3}$.

The curve of ahead pull T_e is approximated by a straight line between a point on the curve R, obtained on calm water and the point of maximum permissible bollard pull. For the ship with fixed pitch propeller the formula for T_e (kN) is presented as:

$$T_e = R_0 (1.35 - 0.35 \frac{V_S}{Vs_{CW}}) \quad (20)$$

The formulae make possible to estimate the decrease in velocity and to estimate the time period required for the ship to enter a shelter port. Fig. 4 and Fig 5 shows the general character of relationship which define (govern, control) the decrease in velocity and its absolute value.

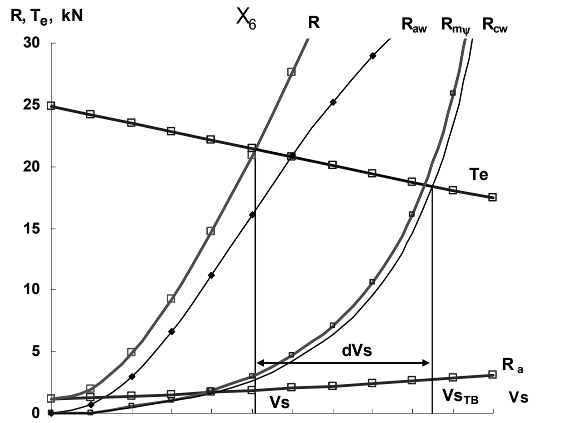

Fig. 4 Additional resistance and decrease of speed on rough seas

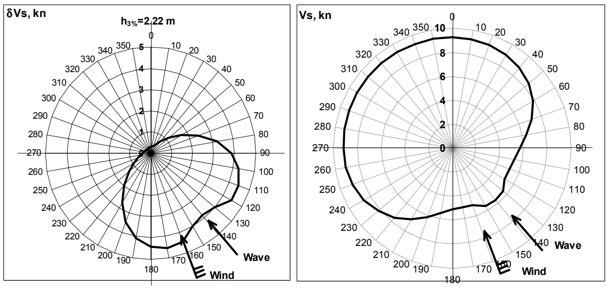

Fig.5. Character of changes of δVs and Vs values for different course angles

4. CRITERIA BASIS

While developing criterion basis for estimating stability under conditions of icing it was assumed that intensive icing is not less dangerous than flooding a compartment. Therefore stability criteria and standards under heavy icing are determined by the following system of inequalities:

- initial metacentric height $h_0 \geq 0{,}05$, m;
- angle of statical heel $\theta_o \leq 20$, deg;
- maximum righting arm $l_m \geq 0{,}1$, m;
- length of positive part of the diagram $\theta_P \geq 20$, deg;
- limiting value of freeboard height: afore $f_1 \geq 0{,}3$ m, amidships $f_2 \geq 0{,}3$ m, amidships side $f_{2S} \geq 0$, astern $f_3 \geq 0{,}3$, m.

The period of navigation before any standard was broken was assumed as critical.

The critical time interval t_{CR} which is decisive for breaking the requirements to ship safety under icing conditions is described as the minimum time interval calculated throughout all the criteria.

Simulation of ship behavior was carried out on the basis of formulae (16)–(21) and t_{CR} was found in accordance with the specified criteria:

$$t_{CR} = min\ [t(h_o),\ t(\theta_o),\ t(l_m),\ t(\theta_P),\ t(f_1),\ t(f_2),\ t(f_{2S}),\ t(f_3)] \qquad (21)$$

t_{CR} was correlated with time of proceeding to a refuge harbor t_S which was presented with regard to decrease in velocity in irregular sea. Safety condition was expressed as:

$$t_{CR} \geq t_S. \qquad (22)$$

When the condition (22) is broken the logical system gives practical recommendations on icing control.

5. SCENARIOS OF SHIP MOVEMENT

When simulating ship dynamics under icing conditions some scenarios of extreme situations have been developed and “performed”. The concept of a logical system enabling to create different scenarios of emerging and developing extreme situations. Analysis and forecast of sequences of development extreme situations is performed by some methods of mathematical simulating on the basis of formulae (10) – (22). Formulation of scenarios is performed using the data of dynamic measurements of the ship and the environment parameters.

Along with traditional strategies which define the space for searching on the basis of single scenarios, more complicated strategies of “generation-check” type have been used. It is convenient to use this approach when the space for searching (rational trajectory of ship motion is not clearly specified. To realize searching in these conditions it is compulsory to generate the next in turn solution (strategy of management) with follow up checking of the results. Practical realization of the strategy “generation-check” involves distribution of functions between the operator (ship master) who chooses particular strategy (course and velocity) and the algorithm of checking which enables analysis of real values of stability in the current situation on the basis of (10) – (22).

Modification of the method “generation-check” may be realized by transition to the strategy “hierarchical generation-checking”. When the latter is used the operator at first develops a partial solution which covers only a part of the problem. In accordance with the results of the solution it is judged how effective the assumed trajectory of the ship's movement is. In case it is effective, at the following step the operator develops a complete solution and the algorithm of checking estimates effectiveness of its realization.

In the example under consideration six different scenarios have been chosen. They define strategies of ship's motion to refuge harbors ***A, B, C*** (fig.6).

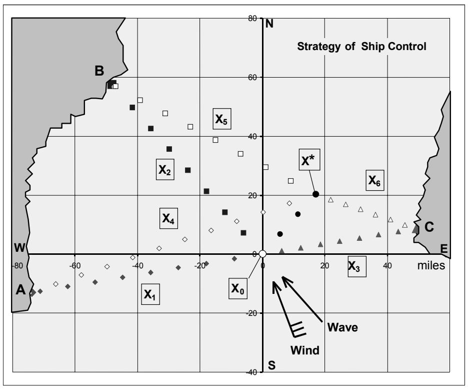

Fig. 6. The situation at the moment of decision making: disposition of the ship in X_0 and X^* and ***A, B, C*** refuge harbors

The first three scenarios X_1, X_2, X_3 characterize ship's movement from initial position X_0. Other scenarios X_4, X_5, X_6 presuppose application of one of the variants of the strategy "generation-check". In compliance with the strategy the ship first makes a maneuver (generation of an immediate possible solution) and moves to some other initial point X^*. This is the initial point for realization X_4, X_5, X_6 strategies of management and checking the results should follow up.

Fig. 6 shows diagram containing information about ship's position in the initial point X_0 (origin), displacement of the ship to the point X^* (dark circle) and trajectories of ship movement to ***A, B, C*** refuge harbors. Trajectories from X_0 are marked by light diamonds, squares and triangles. Trajectories from X^* are marked by dark diamonds, squares and triangles. Distances from the initial point in miles are laid off along axes.

6. RESULTS OF SIMULATION

The results of simulating situations for the $X_1 - X_6$ scenarios under consideration are represented in Tab. 1. The first column contains data referring to initial situation X_0. The column marked by X^* characterized the other initial point. The ship moves to this point from X_0 for realization the strategy "generation-check".

Developing the scenario "generation-check" made possible simulating three additional X_4, X_5, X_6 strategies of ship movement from X^* to ***A, B, C*** ports. The results of simulating the situation "generation-check" permit of significant increasing opportunities to analyze alternatives and make decisions.

We can see from Tab.1 that the most unfavorable situation associated with dramatic decrease in stability occurs when the ship is making to *A* (scenario X_1)**.** It follows from the data that failing to meet requirements to ship safety in this situation is due to two criteria: substantial angle of heel θ_o sometimes as great as 28,7^o and drastic decrease in maximum of righting arms l_m=0,06 m. The situation only becomes worse if the strategy "generation-check" is used. The results of simulating shows in the column for X_5 scenario prove it.

Zero in Tab.2 show that critical time has not been reached. It follows from Tab. 2 that in 6,97 hours the angle of heel due to asymmetrical growing of ice can reach 20 deg. Even earlier in 5,43 hours the deck will immerse. In 6,96 hours the maximum righting arm will equal 0,1 m. In 8.3 hr the ship will reach a refuge harbor. The general outline of changes of analyzed loading, stability and velocity characteristics for the most unfavorable situation X_1 is given in Fig.7.

The data presented visualize very complicated transformations of information in the course of intensive icing. Information dealing with changes in stability indexes in the analyzed scenarios and its correlation with criteria of the adopted system of standardization are of particular importance. Asymmetric icing in the investigated situations has resulted in catastrophic decrease in stability and in a dangerous angle of heel. Maneuvering of ship and passing to situation X_4 (see Tab.1) don't bring to improving stability indexes, and the ship's movement to a refuge harbor ***A*** remains threatening.

Table 1. Comparative characteristics of basic indexes of loading, stability and propulsion for the investigated scenarios

Parameter	X_0	X_1	X_2	X_3	X *	X_4	X_5	X_6
TC, deg		260	320	80	40,0	249,9	299,7	109,8
S, miles		75	75	50	26,5	96,8	75,1	34,3
CB_{WT}, deg	140	140	140	140	140	140	140	140
CB_{TW}, deg	160	160	160	160	160	160	160	160
m, t	0,0	22,9	14,9	19,5	6,8	39,6	20,8	19,9
M, t	160,0	182,9	174,9	179,5	166,8	206,4	187,6	186,7
Xg, m	-0,50	-0,31	-0,90	-0,19	-0,48	-0,08	-0,64	0,12
Yg, m	0,00	-0,31	-0,10	0,22	0,12	-0,34	-0,13	0,23
Zg, m	2,50	2,64	2,59	2,65	2,54	2,77	2,64	2,78
Tf, m	1,86	2,21	1,74	2,25	1,94	2,63	2,02	2,55
Ta, m	2,55	2,67	2,88	2,58	2,60	2,70	2,87	2,45
Tm, m	2,21	2,44	2,31	2,42	2,27	2,67	2,45	2,50
Vs, kn	9,50	8,94	9,18	6,34	8,74	8,68	9,18	5,22
$h_{3\%}$, m	2,22	3,01	3,01	3,01	2,65	3,69	3,54	3,47
$\lvert t_A^o + t_W^o \rvert$, deg	17,00	17,00	17,00	17,00	17,00	17,00	17,00	17,00
ho, m	0,83	0,67	0,88	0,63	0,79	0,53	0,78	0,46
θ_0, deg	0,00	27,64	6,22	18,12	7,98	42,61	9,25	30,88
lm, m	0,39	0,06	0,23	0,11	0,27	0,00	0,15	0,03
θp, deg	99,47	51,85	78,05	63,40	88,03	0,00	70,01	30,93
f_1, m	3,79	3,44	3,91	3,40	3,71	3,02	3,63	3,10
f_2, m	1,09	0,86	0,99	0,88	1,03	0,63	0,85	0,80
f_{2s}, m	1,09	-0,92	0,62	-0,23	0,55	-2,50	0,30	-1,23
f_3, m	1,12	1,00	0,79	1,09	1,07	0,97	0,80	1,22
t(ho), hr								
$t(\theta_0)$, hr		6,97				7,52	7,09	5,37
t(lm), hr		6,96				6,91	7,80	5,03
t(θp), hr						8,79		
$t(f_1)$, hr								
$t(f_2)$, hr								
$t(f_{2s})$, hr		5,43		6,79		6,22	7,28	3,66
$t(f_3)$, hr								
t_S, hr		8,30	8,10	7,92		10,94	8,11	6,69
t_{CR}, hr		5,43	0,00	6,79	0,00	6,22	7,09	3,66

Let's analyze results of accounts on an example of the scenarios X_1.

The critical time is tabulated in Tab. 2.

Table 2. Critical interval

Criterion	t(ho)	$t(\theta_0)$	t(lm)	t(θp)	$t(f_1)$	$t(f_2)$	$t(f_{2S})$	$t(f_3)$	t_S	t_{CR}
Time, hr	0	6,97	6,96	0	0	0	5,43	0	8,30	5,43

7. RISK ESTIMATION AND MAKING DECISIONS

Let's perform a more detailed expert analysis of the data given in Table 1. The ship dimension-less parameter $G=t_{CR}/t_S$ is considered

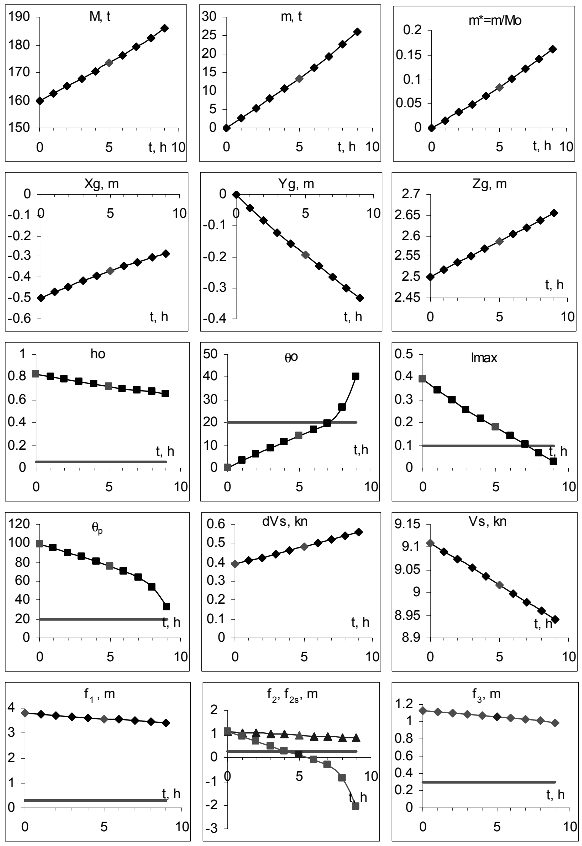

Fig. 7. Changes in ship's characteristics for most unfavorable situation appropriate to ship movement to port A

to be a criterion of safety. This parameter characterizes relationship between critical interval of time t_{CR} and interval t_S of time of a ship proceeding to a refuge harbor. If for the specified strategy no infringements of the accepted criteria of safety are observed, $G=1$ is accepted. In other cases we have $G < 1$. Restrictions on stability C_1 and restrictions on buoyancy C_2 are considered to be imposed restrictions. Requirements to stability diagram h_0, θ_0, l_m, θ_P are restrictions on stability, and requirement to freeboard height f_1, f_2, f_{2S}, f_3 are restrictions on buoyancy. To each of these requirements in the specified strategy there corresponds its inherent critical time, i.e.:

$$C_1 \in [t(h_0),\ t(\theta_0),\ t(l_m),\ t(\theta_P)]\ u \quad C_2 \in [t(f_1), t(f_2), t(f_{2S}), t(f_3)]. \tag{23}$$

Using this information, we shall write down restrictions C_1 and C_2 in the dimensionless form - in relation to a critical interval of time:

$$C_1 \in [t(h_0)/t_{CR}, t(\theta_0)/t_{CR}, t(l_m)/t_{CR}, t(\theta_P)/t_{CR}], \quad (24)$$

$$C_2 \in [t(f_1)/t_{CR}, t(f_2)/t_{CR}, t(f_{2S})/t_{CR}, t(f_3)/t_{CR}]. \quad (25)$$

It is obvious, that the role of restrictions when estimating ship safety on the basis of requirements to stability and buoyancy is not equivalent. Therefore at the stage of expertise it is expedient to introduce factors of importance k_i and k_i* (i =1, …, 4). It is possible to use the following values as such factors:

$$k_1=k(h_0)=0{,}7,\ k_2=k(\theta_0)=0{,}9,\ k_3=k(l_m)=1{,}0, k_4=k(\theta_P)=0{,}5; \quad (26)$$

$$k_1^*=k^*(f_1)=0{,}9, k_2^*=k^*(f_2)=0{,}4,\ k_3^*=k^*(f_{2S})=0{,}8, k_4^*=k^*(f_3)=0{,}6. \quad (27)$$

The received data allow to write down final expressions for restrictions $C_1(x)$ and $C_2(x)$:

$$C_1(x) \in [k_1 t(h_0)/t_{CR}, k_2 t(\theta_0)/t_{CR}, k_3 t(l_m)/t_{CR}, k_4 t(\theta_P)/t_{CR}]; \quad (28)$$

$$C_2(x) \in [k_1^* t(f_1)/t_{CR}, k_2^* t(f_2)/t_{CR}, k_3^* t(f_{2S})/t_{CR}\ k_4^* t(f_3)/t_{CR}]. \quad (29)$$

Thus, on the basis of the given Tab. 1 and formulas (24) – (30) it is possible to construct an expert matrix M_E for realization of the Bellman – Zadeh approach. The algorithm of constructing this matrix consists of the following steps.

Step 1. The criterion of safety $\mu_G(x)$ is allocated and its relative values $G_i(x)=(t_{CR}/t_S)_i$ for the considered strategy (set of alternative) X_i, i =1, …, n are calculated.

Step 2. The restrictions $C_1(x)$ and $C_2(x)$ on stability and buoyancy are formulated on the basis of accepted criteria ratios. These restrictions are represented as relative values (in relation to a critical interval of time t_{CR} for a specified criterion).

Step 3. The expert information in the form of factors k_i and k_i* of importance of restrictions $C_1(x)$ and $C_2(x)$ is entered. The account of these factors makes recalculation of relative values of restrictions for use in an expert matrix possible. If the received ratio exceeds unity the restriction by the appropriate criterion is accepted as equal to unity.

Step 4. The expert matrix determining the initial information for the analysis of alternatives on the basis of the Bellman – Zadeh ap

proach is under construction. In the course of realization of a M_E matrix it is necessary to be guided by the following rules. For each strategy to the lines of restrictions $C_1(x)$ and $C_2(x)$ only the values of criteria ratio are brought which correspond to their least relative values, i.e. for each restriction the worst relative values of criterion $\mu_{C1}(x)$ = $min\ C_1(x)$ and $\mu_{C2}(x)$ = $min\ C_2(x)$ in view of factors of importance are chosen.

The expert matrix derived in this way is submitted in Tab. 3

Table 3. Expert M_E matrix

Xi	X_1	X_2	X_3	X_4	X_5	X_6
$\mu_G(x)$	0,65	1	0.86	0.57	0.87	0.55
$\mu_{C1}(x)$	1	1	1	0.71	0.90	1
$\mu_{C2}(x)$	0.80	1	0.80	0.80	0.80	0,80

Note: the strategy X_4 here is not considered, as it assumes short-term transition from an initial point 0 (light point) to point X* (dark point) in a Fig. 7.

Using the operation of capture of the minimum for the decision of the considered task we receive (Tab. 4).

Table 4. Results of the analysis of expert matrix data

X	X_1	X_2	X_3	X_4	X_5	X_6
$\mu_G(x)$	0,65	1	0.80	0.57	0.80	0.55

Applying the operation of capture of the maximum to Tab. 4, we receive, that in the considered task the strategy X_2 (movement of a ship to port B) is optimum, therefore manoeuvre of a ship in the course of transition to point

X^* will not result in increase of ship safety under the conditions of icing.

8. CONCLUSION

The offered approach to modeling of ships dynamics an intensive icing is based on a combination of methods of classical mathematics and models of fuzzy logic. This approach has the great importance to construction of algorithms of acceptance of the decisions in conditions of uncertainty and incompleteness of the initial information.

The developed computing technology takes into account features:

- the form of the case, loading and surface of a ship architecture;
- dynamics of development of an icing;
- change of external conditions (temperature of air and water, scenarios of storm development, hydro– aerodynamic resistance on waves);

The results of research can be used:

1. In onboard intelligence systems of a safety of navigation.

2. In research designing – in accounts of ship dynamics at an icing.

3. At an estimation of risk of the accepted decisions - at the comparative analysis of extreme situations.

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