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RESEARCH ARTICLE

Problem statement on the vessel braking within ice channel

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Abstract

Sailing within the ice channel that assisting icebreaker tracks is usual for difficult ice conditions in the Northern freezing seas and the Arctic region. There is the danger of emergency, namely, the collision with an icebreaker or the ahead vessel, when ones stop before insuperable ice obstacle or because the engine trouble. The paper contents analysis of the vessel braking process and formulation of the equation that gives possibility modelling this process and evaluating the distance that is necessary for safe stopping of vessel in dependence on its characteristics and ice conditions. Outcomes of investigation will be applicable for the caravan of cargo vessels forming while the icebreaker assistance.

Keywords: cargo vessel; ice navigation; icebreaker assistance; ice channel; collision; braking

1 Introduction

With the development of navigation in the ice condition, convoy operations become more and more frequent in the Arctic regions, when the ice class of vessel is not enough for unassisted sailing or when vessels do not have ice classification. Moreover, the ice-breaking assistance can optimize the route and efficiency of shipping in the trans-Arctic navigation [1]. However, the risks of emergency damages and even wreck of vessels accompany sailing of cargo vessels in ice conditions of the polar seas even with the icebreaker assistance [2, 3]. Therefore, adequate forming of caravan is the main safety facility.

In difficult ice conditions, navigation of cargo vessels is carried out in the caravans, which the icebreaker steers (as the leader). Vessels behind the icebreaker sail within the laid by the icebreaker channel filled by broken ice, on specified distance one after another [4, 5]. As result, the risk of accidents arises, namely, collisions of ships, if the lead icebreaker slows down or will stop

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movement because of a meeting with difficult-to-overcome ice obstacles and if any vessel in a caravan will be gripped by ices fields or in case of its engine trouble.

Providing the safe navigation of the caravan requires solution of following main problems:

(i) Formation of vessels within caravan in dependence on their ice category (ice classification), dimensions, hull strength and engine power.
(ii) Selection of the speed for the whole caravan and each vessel sailing.
(iii) Selection of the distance (space) between an icebreaker and first vessel and then between next vessels.
(iv) Organization of the navigation support and service on the navigation bridge.

Various problems of the ice navigation with an icebreaker assistance are actual for the Arctic seas and freezing northern seas and therefore they are subject of numerous studies.

Small ice floes fill the ice channel, and the vessel does not have possibilities for sailing with same speed as on open water. Therefore, the speed of the most slow-speed vessel determines the speed of whole caravan. Topaj et al [1] present solution for the speed selection within ice channel after icebreaker. Ice characteristics within channel, dimensions and engine power of vessel and icebreaker are the base for solution. The mathematical model and special diagram are developed and recommended for speed selection.

For prevention the collision, a vessel should brake and stop movement by a backspacing of propellers rotation on ”backing”. If the distance, which is required to a full stop of ship, is more than distance to an icebreaker or an interval between vessels within a caravan, the collision will occur. (As an exception, it is possible to consider the assistance for the large capacity vessels which beam exceed the channel width and the necessity to break the ice channel edges helps the braking [6]). In addition, there is a risk of being stuck in the ice, if the distance is too large, the ice floes re-fulfils the ice channel, and it closes.

Selection of the minimal distance between an icebreaker and escorted vessel is very complicated problem, and the practical experience is the base for it solution at present. Russian guidance [7] entrusts captain of the leading icebreaker with setting intervals between vessels on base of his experience and in dependence on the ice conditions. Canadian guidance [14] recommends the preliminary trials of an escorted vessel braking before the assistance start.

The safe distance between icebreaker and assisted vessel (ship domain) depends upon the ice condition on the route of escort. Analysis of the ship domain and ice conditions relationship was performed on the base of the AIS data for northern water area of the Baltic Sea [8].

Collisions of escorted vessels with an icebreaker or other ship in convoy are real emergencies and occur owing to a failure to observe the recommended safe distance owing to ”human factor” or variation of ice conditions (The methodology and analysis of these factors comparative role are shown in references [9, 10]). Therefore, it is applied the special simulators for training navigators for sailing after icebreaker and as a part of caravan. The software of simulator includes the analytical model of the ship sailing within channel and algorithms for the safe distance definition and maintenance while variation the sailing and ice conditions. Solution of these problems is the actual subject of investigations for many researchers [11–13]. Proposed models content the interval between vessels within caravan as defined from experience parameter and are aimed at its keeping.

Actually, required safe distance of a vessel stop depends on many factors, among which there are dimensions of hull, type and capacity of the power plant, a design of rudder-propulsion complex, and the sizes of the ice channel, a thickness of ice and ice floes concentration. The ”human factor” plays also an important role, namely, the timetable of the navigator for decision-making and performance of a backspacing of propellers rotation. The combination of these factors defines risks of emergency, and the knowledge of all complex factors occurring at braking of the ship is required for the safe distance between icebreaker and vessels definition and management.

For the problem solution, special studies of the sailing and braking of vessels within the ice channel, including a situation of compression of ices are necessary. It supposed the problem has decision as combination of the theoretical analysis, development of mathematical model, numerical simulations and physical modelling—experiment in the ice-towing tank. Experimental data will give the possibilities to specify mathematical model, to estimate a distance of braking of a vessel depending on characteristics of a vessel and ice conditions, and to develop recommendations for caravan construction at the ice pilotage.

Problems of the movement vessel reverse and the propeller thrust on ”backward” regime has been studied formerly as applied for sailing in free from ice cover conditions [19, 20]. It is suitable to apply these outcomes for the ice covered water areas.

This paper contents the results of preliminary studies of this problem, namely, conceptual analysis of the braking of vessel process that gives understanding of the acting on vessel forces and their dependence upon characteristics of vessel hull, power plant capacity and rudder-propeller complex peculiarities. Resistance for vessel movement includes the usual frictional one and ice resistance that depends on ice conditions in the channel. Formed on this base equation of the vessel movement has taken into account all forces that define braking of vessel. For this equation of motion, all initial and boundary conditions were determined. The most complicated problem for solution is parameterization of the propeller thrust on the reverse regime considered in dependence on the rudder-propeller construction.

Stated results would be base for analytical investigation and computer modelling of the cargo vessel braking within ice channel after the leading icebreaker both for single pilotage and on the caravan.

2. Statement problem

Some kind of the ice obstacles stops the icebreaker and following after vessel should apply the braking by means of the propellers reverse for the stopping. If the distance between icebreaker and vessel is not large enough or the decision about braking is accepted with unacceptable delay, the collision can realize. As result, the vessel will damage the fore body.

It is impossible to increase the distance between vessel and an icebreaker over some limit because the drift of ice cover under action of wind and current that can close the ice channel and disable the sailing of the vessel.

Therefore, the some ”optimal” distance between an icebreaker and following vessel exists that provides effective and safe sailing. This distance depends upon three factors:

(i) Ice condition on the water area were the icebreaker pilotage realizes.
(ii) Propulsive performance of vessel while regime of the propellers reverse.
(iii) Reaction time of the navigator on the nonreversible change of navigability.

For this problem solution, it is reasonable to analyse following situation. The vessel sails after an icebreaker within filled by small broken ice floes channel. In certain time, the danger of the collision with icebreaker appears. The vessel changes the regime movement from ”forward” on ”backward” in order to interrupt movement and to avoid the collision. Problem of studies is the valuation of distance that vessel can sail to a stop, that is the decreasing its velocity until ”0”.

This distance depends on two main factors:

(i) Displacement, form of hull, initial regime of sailing (velocity), the ice propulsion within the ice channel, the propeller thrust on ”backward” regime and time for engine reverse.
(ii) Characteristics of the ice channel including its width, ice thickness, sizes of ice floes and concentration, and the intensity of ice compression.

For problem solution, it requires following:

(i) Compose the equation of movement.
(ii) Determine and parameterize all components of the equation.
(iii) Form initial conditions and values of variables.
(iv) Determine the changing of all parameters from which the running out of vessels depends on.

Future, it is possible to proceed the solution of the motion equation with systematic variation of all parameters. Obtained results will give possibilities to create the diagrams and identify the required dependences.

3. Derivation of the motion equation

It is supposed that the vessel movement is rectilinear and directed toward axis OX and coordinate x is location vessel at time t. The propeller thrust forces on vessel, which decreases until ”0” value, sometime is absence and then change direction on backward direction. Secondly, there is resistance for movement depending on velocity of vessel and ice condition within ice channel. Besides, the vessel possesses own inertia and an inertia of the attached water and ice masses. Fig. 1 presents the scheme of process and forces effecting on vessel.

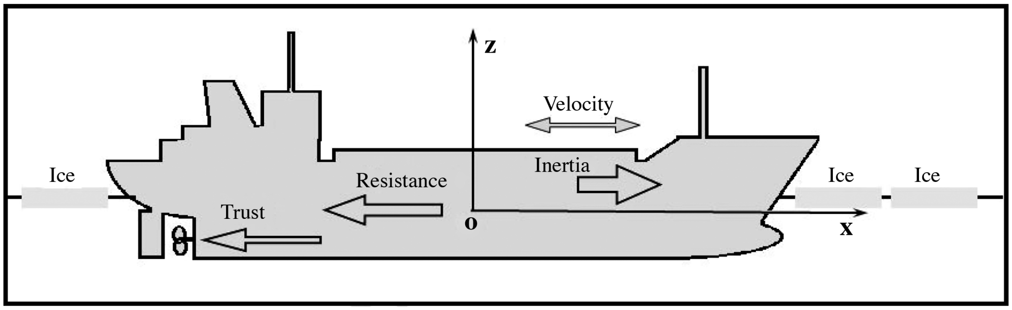

Fig. 1. Scheme: the braking of cargo vessel and effecting forces

The equation of movement of a vessel has the following appearance:

$$(m_s + \Delta m_w + \Delta m_{ice})\, a_x = P\,(t) - R_w\,[v_x\,(t)] - R_{ice}\,[v_x\,(t)]\,. \tag{1}$$

In this equation, t means time; a_x means acceleration of vessel; v_x means its velocity; m_s means mass of vessel; Δm_w means added mass of water; Δm_{ice} means added mass of ice; P means thrust of propeller; R_w means resistance of water for movement; R_{ice} means ice resistance because the ice floes within channel.

It is possible to consider as negligible the added mass of the ice floes interacting with vessel hull, because it is infinitesimal in comparison with the added mass of water. Density of sea ice is close to density of seawater and the ice surface rise above the equilibrium water level compensates the difference of their densities. Therefore, this part of ice cover does not increase the added mass of seawater. Besides the concentration of ice floes within an ice channel is less than 100% always.

Therefore, equation (1) has following form :

$$(m_s + \Delta m_w)\, a_x = P\,(t) - R_w\,(v_x\,(t)) - R_{ice}\,(v_x\,(t))\,. \tag{2}$$

Applying standard notification of the mathematics, following symbols has introduced in this equation:

$$a_x = \frac{d^2 x}{dt} = x'', \quad v_x = \frac{dx}{dt} = x'. \tag{3}$$

As result equation (1) has following form:

$$(m_s + \Delta m_w)\, x'' = P\,(t) - R_w\,(x') - R_{ice}\,(x')\,. \tag{4}$$

Future, it is required to determine the components of this equation.

4. Mass of vessel and added mass of water

Displacement of vessel defines its mass and following equation presents it:

$$m_s = \gamma_w\, D. \tag{5}$$

In this equation D is displacement of vessel; γ_w is density of seawater.

The added mass of water depends on the hull dimensions and is proportional to the mass of vessel [18, 20]

$$\Delta m_w = \lambda_{11}\, m_s. \tag{6}$$

The proportionality coefficient λ_{11}, coefficient of the added mass of water for cargo vessels, can be evaluated using following equation [20]:

$$\lambda_{11} = \frac{2\,T}{L}\left[0.18 + \left(\frac{B}{L}\right)^2\right](0.624 + 0.72\,\delta)\,. \tag{7}$$

In this equation L is length of hull, B is beam breadth; T is draught; δ is coefficient of total hull fullness.

5. Resistance for movement of vessel

Total resistance for movement of vessel is sum of the resistance from friction of water on the hull and the ice resistance that arise owing to the interaction of hull with ice floes in the ice channel. (Energy spent for the vessel wave forming is negligibly quantity in the ice conditions [8]). These components are studied and can be defined using known methods.

For the friction resistance it is suitable to apply following equation [15]:

$$R_{fr}\,(v) = \frac{1}{2}\zeta_{fr}\,(v)\;\gamma_w\, v^2\, \Omega_s. \tag{8}$$

In this equation ρ_w is mass density of the sea water; Ω_s is area of the wetted surface of vessel hull; ζ_{fr} is friction coefficient that depend on Reynolds number Re and therefore upon velocity of movement and therefore on time. For turbulent regime friction within the boundary layer on hull, following equation defines coefficient of friction [15]:

$$\zeta_{\text{fr}}(v) = \frac{0.455}{\{\lg[\text{Re}(v)]\}^{2.58}}. \quad (9)$$

For the ice resistance for vessel moving within the ice channel filled by small ice floes following equation exists [17, 21]:

$$R_{\text{ice}}(v) = k_0\, g\, \gamma_{\text{ice}}\sqrt{l_f\, h_{\text{ice}}}\, B\left\{\frac{B}{4}\left[k_1\left(1 + 2\, f_d\, \varphi_B \frac{L}{B}\right)\right]\right.$$
$$\left. + k_2\sqrt{l_f\, h_{\text{ice}}}\,(f_d + \varphi_B \text{tg}\alpha_B)\,\text{Fr} + k_3\sqrt{l_f\, h_{\text{ice}}}\frac{L}{B}\text{tg}^2\alpha_B \text{Fr}^2\right\}. \quad (10)$$

In this equation, h_{ice} is ice thickness; l_f is specific dimension of ice floes; φ_B is coefficient of the foreline part of design waterline fullness; α_B is slope of the foreline in relation to the diametral plane; $k_0 = \pi/2$, k_1, $k_2$and k_3 are empirical coefficients depended on the ice floes concentration within channel and relative width of channel; Fr is Froude number.

In that way, the total resistance force depends on dimensions and form of hull, ice conditions within channel, velocity of movement and is directed in opposite for movement direction. The main assumption is the independence of resistance on an acceleration that originates when the vessel begins braking.

6. Propeller thrust while braking

Propeller thrust while braking should be directed against the direction of the vessel movement. For this purpose, it is required to realize the reverse of the engine–propeller–rudder complex. On vessels that navigate in the ice conditions, there are following types of this complex:

(i) Traditional variant of complex that has propeller designed for the most effective operation on the ice-free water areas and the ice navigation has the relative short time.

(ii) Propeller designed special for the ice navigation. Such propellers have the blades with symmetrical toward their axis form in plane and almost symmetrical profile of cross-section. It provides the equal-effective (means of thrust) the propeller work on the ”forward” and ”backward” regimes. The type propellers is employed on the icebreakers and vessels meant for the ice navigation in the Arctic seas.

(iii) Design of the propeller-rudder complexes AZIPOD provides the 180° turn and therefore the equal-effective the propeller work on the ”forward” and ”backward” regimes without the reverse of engine.

While the reverse regime the propeller has the specific conditions for work because its direction of rotation changed on ”backward” as the direction of translation remains ”forward”. Therefore, the mode of the propeller blade work changes substantially: the detached flow replaces the streamline flow. Unfortunately, the characteristics of propellers while work on regime of reverse do not studied adequately [16] and therefore special analysis of this problem is required.

Propellers with traditional design because the asymmetric form of blades draw the less thrust in the reverse regime. Therefore, they have the most distance of the braking and the more risk of collision within the ice channel. It is reasonable to study problem for them in the first place.

For the modelling of the propeller thrust in regime of reverse, it is also necessary to take into account the change of the propeller—hull interaction that is absent of the trailing wake for propeller and the thrust-deduction fraction for hull.

7. Vessel-braking process

It is possible to divide the braking of vessel process on three periods: moving ”forward” on stable regime, the reverse of the engine on the counter-rotation and running of the engine in this regime until stopping the vessel.

Fig. 2 [19] presents the results of the engine running investigations while reverse and braking of a vessel in the ice-free conditions. (Vessel specification, dead weight 47 000 tonnes, power of engine 8350 kW on 127 r/min, full speed 14.5 knots, variable pitch propeller with pitch 0.9 m). Following nominations are applied, n the velocity of the propeller rotation; N the power of engine; and v the vessel speed after the engine stopping on ”forward” regime and its running on ”backward” regime. It is possible to separate out the following specific periods of the engine running:

- 0–10 second: the engine shuts down;

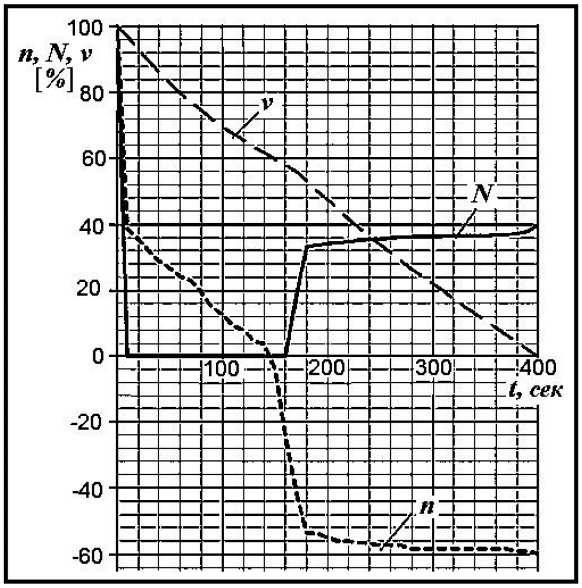

Fig. 2. The rate of propeller rotation *n*, engine capacity *N* and vessel speed *v* variation while braking regime [19]

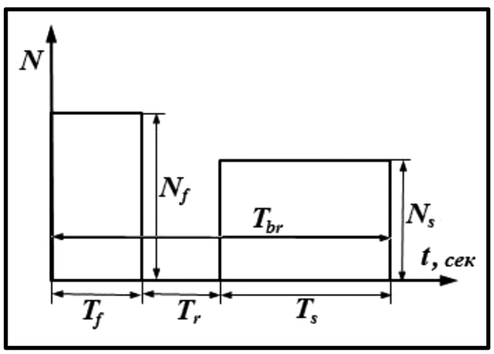

Fig. 3. Model of the engine capacity variation during braking process

- 10–160 second: reverse of engine on the counterrotation;
- 160–80 second: acceleration of the engine;
- 180–400 second: the engine running on ≅ 38% capacity until motion dwell.

Fig. 3 presents the proposed variant of the engine running regime variation during braking of vessel. Following notation are applied, N_f the capacity of engine on ”forward” regime; T_f the time to make decision about braking and engine shutdown; T_s the time to the engine reverse; N_s the engine capacity on ”backward” running; T_s the time of the engine ‘backward’ running until the vessel movement dwell.

It is reasonable to apply this diagram as base for the vessel braking within an ice channel modelling. Time of the engine shutdown is short and therefore is negligible one.

The engine capacity and the propulsive coefficient define the propeller thrust, if the action curves of propeller on the reverse regime are known. Therefore, stated image of the engine regimes running give possibilities to evaluate the propeller thrust in dependence on the velocity and direction of a vessel motion and apply it for the equation (4) solution.

8. Conclusions

On the base of performed analysis of process of the vessel braking within ice channel, the equation of a vessel movement has been derived. Equation takes into account the forces effecting on vessel including the resistance for movement, the propeller thrust and attached water mass. Main component of resistance: the ice resistance of floes filling channel can be defined using known data. It depends on the dimensions and form of vessel hull and the ice conditions within ice channel including ice thickness, floes sizes and its concentration. This gives possibilities to evaluate the distance of the vessel braking for various initial data.

Base for the motion equation solving is the time dependence of the vessel engine running that takes in to account three main periods: decision making, reverse of engine and engine running on ‘backward’ regime until the vessel movement dwell.

Stated results can be applied for the modelling of the vessel braking within the ice channel after assisting icebreaker or ahead cargo vessel. Systematic computation will give possibilities to develop the special nomograms that will be base for the safe distance between ships within convoy definition in dependence on ship characteristics and ice conditions. Model can be also base for special simulators of the conning bridge for training of the navigators for navigation in the ice-covered seas.

Nomenclature

B	Beam breadth [m]
D	Displacement of vessel [m^3]
L	Length of hull [m]
N	Power of engine [W]
N_f	Capacity of engine on ”forward” regime [W]
N_s	Capacity on ”backward” engine running [W]
P	Thrust of propeller [N]

R_w	Resistance of water [N]
R_{ice}	Ice resistance [N]
T	Draught of vessel [m]
T_f	Time to make decision about braking and engine shutdown [s]
T_r	Time to the engine reverse [s]
T_s	Time of the engine ”backward” running [s]
a_x	Acceleration [m/s^2]
g	Gravity acceleration [m/s^2]
h_{ice}	Ice thickness [m]
$k_0 = \pi/2$, k_1, k_2 k_3	Empirical coefficients
l_f	Specific dimension of ice floes [m]
m_s	Mass of vessel [kg]
Δm_w	Added mass of water [kg]
Δm_{ice}	Added mass of ice [kg]
n	Velocity of the propeller rotation [1/s]
t	Time [s]
v_x	Velocity [m/s]
Ω_s	Area of the wetted surface of vessel hull [m^2]
α_B	Slope of the foreline in relation to the diametral plane
γ_{ice}	Density of ice [kg/m^3]
γ_w	Density of sea water [kg/m^3]
δ	Coefficient of total hull fullness
λ_{11}	Coefficient of the attached mass of water
ρ_w	Mass density of the sea water [kg·s^2/m^4]
φ_B	Coefficient of the waterline fullness
ζ_{fr}	Friction coefficient
Fr	Froude number
Re	Reynolds number

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References

1. Topaj AG, Tarovik OV, Bakharev AA et al. Optimal ice routing of a ship with icebreaker assistance. *Appl Ocean Res* 2019; **86**:177–87.
2. Goerlandt F, Goite H, Valdez Banda OA et al. Analysis of wintertime navigation accidents in the Northern Baltic Sea. *Saf Sci* 2017; **92**:66–84.
3. Goncharov VK, Klementieva NYu, Sazonov KE. Russian brings experience to winter navigation safety. *Nav Archit* 2011; 56–8.
4. Arikainen AI. *Navigation at the Arctic Seas*. Moscow: Transport, 1990.
5. Shatzberger EM. *Tactics of the Ice Navigation: Arctic Ice Routes*. Saint Petersburg: Articom, 2011.
6. Dobrodeev AA, Klementyeva NYu, Sazonov KE. Large ship motion mechanics in “narrow” ice channel. *Polar Mechanics*. In: *IOP Conference Series: Earth and Environmental Science*, Novosibirsk, Russia, 2018, 7.
7. *Ice Navigation*. Saint Petersburg: Palmali Group, 2011.
8. Goerlandt F, Montewka J, Zhang W et al. An analysis of ship escort and convoy operations in ice conditions. *Saf Sci* 2017; **95**:198–209.
9. Zhang MY, Zhang D, Fu SS et al. Safety distance modeling for ship escort operations in Arctic ice-covered waters. *Ocean Eng* 2017; **146**:202–16.
10. Zhang M, Zhang D, Goerlandt F et al. Use of HFACS and fault tree model for collision risk factors analysis of icebreaker assistance in ice-covered waters. *Saf Sci* 2019; **111**: 128–43.
11. Khan B, Khan F, Veitch B. A cellular automation model for convoy traffic in Arctic waters. *Cold Reg Sci Technol* 2019; **164**:1–8.
12. Zhang W, Goerlandt F, Kujala P et al. A coupled kinematics model for icebreaker escort operations in ice-covered waters. *Ocean Eng* 2018; **167**:317–33.
13. Zhang W, Zou Z, Goerlandt F et al. A multi-ship following model for icebreaker convoy operations in ice-covered waters. *Ocean Eng* 2019; **180**:238–53.
14. Navigation in ice covered waters. In: *Ice Navigation in Canadian Waters*. Ottawa: Canadian Coast Guard, 2012, 81–131.
15. Voitkunsky YaI. *Resistance of Water for Vessels Motion*. Leningrad: Sudostroenie, 1988.
16. Basin AM, Miniovich IYa. *Theory and Design of the Screw Propellers*. Leningrad: Sudostroenie, 1963.
17. Kashtelian VI, Pozniak II, Ryvlin AYa. *Ice Resistance for Vessel Motion*. Leningrad: Sudostroenie, 1968.
18. Korotkin AI. *Added Masses of Vessel: Reference Book*. Saint Petersburg: Sudostroenie, 1986.
19. Ravin AA, Amirly EA. Modelling of the emergency braking of vessel. *Sudostroenie* 2017; **5**:12–16.
20. Solarev NF, Beloglazov VI, Tronin VA. *Ships and Caravans Control*. Moscow: Transport, 1983.
21. Tsoy L. Modeling of vessel movement in a channel broken up by icebreaker. In: *The Seventh International Conference on Port and Ocean Engineering Under Arctic Conditions*, Espoo, Finland, 1983, 654–63.