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INTERACTION OF SHIPS UNDER TRAFFIC WITHIN NAVIGABLE ICE CHANNEL

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ABSTRACT

At intensive winter navigation, the ships should separate under movement on opposite courses or make overtaking of slowly moving cargo vessels in the water areas covered with ice. Side force and yawing moment that appear on ship hull under these manoeuvres are different from items on the water area without ice cover. Therefore, it is necessary to allow them at navigation and for training on simulators.

At carrying of these manoeuvres in the free from ice water area, the distortion of the structure of flow in changeable space between hulls of vessels produces the side force and yawing moment. In ice conditions, the ice floes between hulls and outside are the major factors defining values and direction of side force and yawing moment. Ice loads on the ship hull exceed considerably the loads caused by water flow around hull. Experiments in the ice basin performed early have shown that besides increase of side force and yawing moment modules the variation of their action directions occurs during the separation of ships.

Paper contains the analytical approach to the solution of stated problem, namely, parameterization of ice effect on vessel hull at interaction with opposite or overtaken ship. The base assumption for mathematical model development is the variation of ice floes concentration around hull because of space within ice channel decrease, when other vessel hull moves along modelled vessel. Results of computations, namely, character of variation of side force and yawing moment during passage along overtaken ship and dependence of the peak values of side force, ice resistance and yawing moment on beam distance between vessels and thickness of ice are presented in paper.

INTRODUCTION

For maintenance of ice navigation during wintertime, icebreakers create the wide channel in the fast ice cover at water areas near to ports with intensive traffic of vessels, in which vessels can move in both directions independently without icebreaker pilotage. Such situation is characteristic one for east part of the Gulf of Finland and the Siberian river Ob mouth in the Kara Sea.

Navigable ice channel provides an opposite movement of large capacity vessels and overtaking of slowly moving vessels. Owing to the intensive traffic, maneuvers of moving vessels on opposite courses or overtaking are carried out very often in such areas. The width of ice channel is limited; therefore, at maneuvering of vessels the accidents are possible: collision of vessels or vessel blow in a channel edge that can cause damages of vessel hull and, probably, the crude oil or fuel spillage.

It is known, that at approach of moving vessels on open water, the side forces directed to space between hulls and the yawing moments arise that can cause collision of vessels. Regularities of this phenomenon are investigated and used in training simulators to train navigators for ship control in considered situation.

At vessel navigation through the ice cover, the forces caused by interaction of the hull with ice floes exceed considerably the forces connected with water flow around the hull. Therefore, there are reasons to consider that character of interaction of vessels at movement in ices conditions essentially differs from interaction on open water.

Really, experiments performed in the ice-towing tank have shown that the variation of side force in the course of opposing movement and overtaking has sign-variable character with considerable pulses [Goncharov et al, 2009; 2009]. This phenomenon has been explained, accordingly, with affect on vessel hull of all ice floes mass in space between hulls of moving vessels and with impacts of separate ice floes in the hull.

To train navigators for ship control during opposing or overtaking in ice conditions, it is required to develop the mathematical model giving possibility to estimate the side force and yawing moment and suitable for usage in navigation simulators. On base the model, it is possible to estimate the minimal safe beam distance between vessels and then required safe width of the navigable ice channel.

Special phenomenological and then theoretical analysis was performed with purpose to develop the method for computation the side force and yawing moment arising when vessels perform the opposite movement and overtaking within the ice channel.

Some results of study problem were presented early [Goncharov et al, 2012]. Paper contents more detailed reasoning and description of analytical model for calculation of interaction of vessels under overtaking within navigable ice channel and the results of computation cycle that illustrate the adequacy of model to a problem in view.

STATEMENT OF PROBLEM AND REASONING OF MODEL

The navigable ice channel is not stable rout for navigation. Owing to frosts, the filling channel brush ice freezes together, and forming solid ice opposes to traffic, therefore icebreakers repair periodically the ice channel. Eventually the thickness freezing together ice floes within the channel begins to exceed considerably a thickness of an ice cover surrounding the channel and icebreakers create the new ice channel, settling down in parallel previous one. Figure 1 presents the scheme of cross-section of the navigable ice channel at different stages of its existence: after a laying of the channel by icebreaker (*a*) and in a stage of its usage end (*b*).

The most available for analytical description is interaction of vessels within "fresh" navigable ice channel, when separate ice floes occupy uniformly some part of water surface between edges of channel. It is possible to characterize the ice conditions within channel by three parameters: average dimension – r and thickness - h_{ice} of ice floes and ice concentration s.

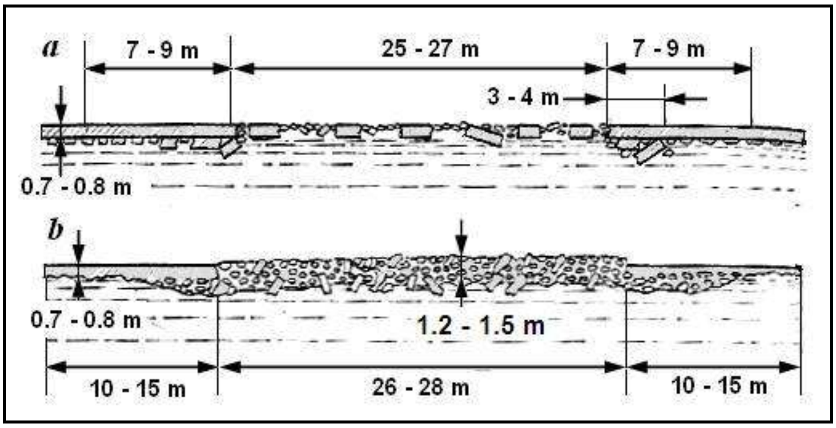

Figure 1. Cross section of fresh (*a*) and old (*b*) navigable ice channels.

Appearance of vessel among ice floes change the ice concentration in depend on the hull beam, width of channel and total area of ice floes relation in the section of channel under consideration. If vessel navigates nearer to some edge of channel, the ice concentration along respective board will be more than on opposite side. Figure 2 shows this situation: ice concentration s_0 before vessel is less than concentration s_1 between left board of vessel and edge of channel, and s_1 is less than concentration s_2 between right board and edge of channel. Therefore, the difference between ice concentration s_1 and s_2 will result in the ice resistances on vessel boards and this difference will determine the affect of channel edge on vessel movement

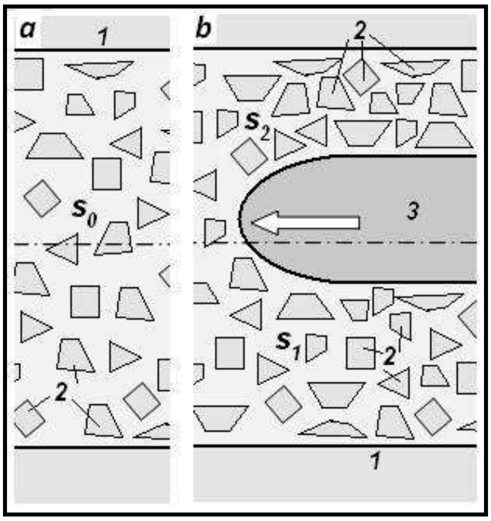

Figure 2. Scheme of the ice concentration changing within ice channel under motion of ship. Notations: *1* – edge of channel, *2* – ice floes, *3* – ship hull; s_0 – ice concentration in the channel, s_1 and s_2 - ice concentrations between hull and channel edges.

Similar approach was applied for parameterization of the interaction of vessels moving within an ice channel. Figure 3 illustrates this model. It is supposed to simulate the opposing vessel (or overtaking one) by means of narrowing of the channel width. The ice concentration increases in inverse proportion to the beam distance between vessels *d* and distance between reverse board and edge of channel *l*. The speed of vessel at issue is equal to sum of both vessels speed under opposite motion and equal to their difference under overtaking.

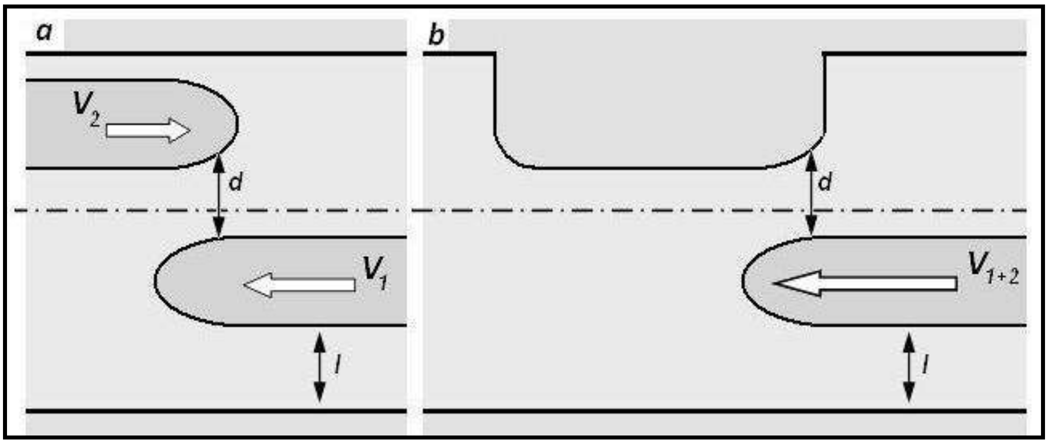

Figure 3. Scheme of simulation of opposite ship by means of narrowing of the ice channel.

Thus, developed conceptual model allows parameterize the side force and yawing moment that arise under interaction of vessels within ice channel by the difference of ice resistances on left and right boards of vessel at issue. The model of ice resistance of vessel that takes into account the ice concentration is necessary to apply for develop mathematical model of interaction of vessels moving within the ice channel filled by brush ice.

ANALYTICAL STUDY OF PROBLEM

To calculate the ice resistance of vessel that navigates in the broken ice floes (Kashtelian et al, Ryvlin and Heisin, 1980) in the middle of compacted ice cover the following formula was recommended:

$$R_{Ice} = 10\left[\rho_{Ice}\sqrt{rh_{Ice}}\left(\frac{B}{2}\right)^2 k_1\left(1+2 f_{ID}\,\beta\frac{L}{B}\right)+k_2\,\rho_{Ice}\,rh_{Ice}\,B\left(f_{ID}+\beta tg\alpha_0\right)Fn + + k_3\,\rho_{Ice}\,rh_{Ice}\,L\,tg^2\alpha_0\,Fn^2\right]. \quad (1)$$

In this formula R_{Ice} - ice resistance of the broken ice (without water resistance); rh_{Ice} – average size of ice floes; h_{Ice} – average thickness of ice floes; ρ_{Ice} – density of ice; f_{ID} – ice friction factor against hull plating; L - length of the vessel; B – width of the vessel; β - waterline area coefficient; α_E – angel between tangent to waterline at nose and center line; Fn – Froude number; k_1, k_2, k_3 – empiric coefficients depending on ice concentration. Average dimension of ice floes rh_{Ice} for sea ice is relatively constant. For small ice floes within ice channel made by an ice-breaker the value of the parameter rh_{Ice} is set by the following formula depending on ice cover thickness, in which the channel is made:

$$rh = 0.54h^2 + 0.45h. \quad (2)$$

Coefficients k_3 = 4.2. Coefficients k_1, k_2 depend on the ice concentration, are determined by the following formulas (ice concentration - s is given in balls):

$$k_1 = 0.01\left(0.25s^2 - 2.15s + 3.9\right),$$
$$k_2 = 0.113s^2 - 0.305s + 0.46. \quad (3)$$

The researches (Kashtelian et al, Ryvlin and Heisin, 1980) had shown the coefficient k_1 also depends on the relative width of the channel made by the icebreaker: $n = B_C/B$, where B_C - channel width, B - vessel width. Thus, coefficient k_1 depends on two factors: ice concentration s and relative size of the channel (it is more convenient to apply the inverse value $n' = 1/n = B/B_C$) and it is necessary to present it in following form:

$$k_1(s, n') = k_{11}(n') + k_{12}(s), \qquad (4)$$

Here k_{12} is determined by formula (3) and

$$k_{11}(n') = 0.01[61.02n' - 57.83n'^2], \quad 0 < \frac{B}{B_c} \leq 1. \qquad (5)$$

In case of on-coming and overtaking distance between vessels changes, therefore value of coefficient k_1 changes, so it is possible to calculate forces affecting the ship's hull. Figure 4 presents the schema of the overtaking and accepted notations.

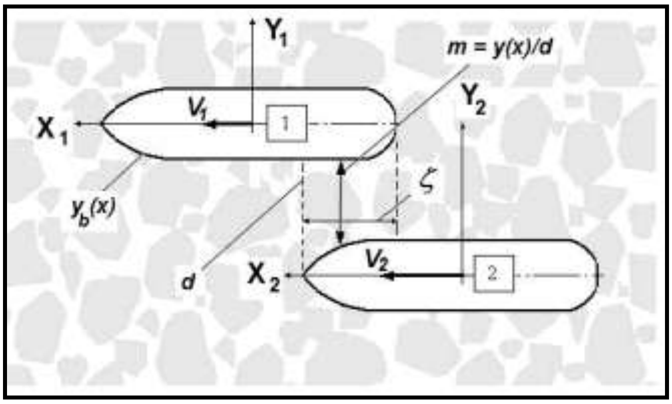

Figure 4. Scheme of overtaking vessel in wide ice brush field.

When considering separate parts of the waterline, it can be noticed that the local value of relative channel width is changed from 0 on the stem post to the value n' amid ship. Then we can suppose that a certain average value is chosen as $k_1(s, n')$ using the concept of primitive function can be fixed as follows:

$$k_1(n') = \frac{1}{n'}\int_0^{n'} q(m)dm = \frac{1}{n'}\{Q(n') - Q(0)\} = \frac{1}{n'}Q(n'). \qquad (6)$$

Here $m = y(x)/d$ - the current value of inverse relative channel width n', d - distance between the center line of the vessel and edge of the channel, $Q'(m) = q(m)$.

Using the forms (5) and (6) it is possible to find following formula:

$$q(m) = 0.01\left[122.04m - 173.49m^2\right]. \qquad (7)$$

When overtaking of the standing vessel, value ζ is the distance taken from the stern of the standing vessel to the stem post of the overtaking vessel. Hence at the distance between ships' hulls of ζ long the broken ice floes will be constricted. The effect of the standing vessel on the overtaking vessel is similar to the influence of the ice channel edge; this effect can be described using the coefficient $k_1(s,n^{'})$

Elementary side force and resistance force can be calculated using the following formulas:

$$\begin{gathered} dF = k_1\left(x\right)\rho_{Ice}\sqrt{rh}\,y\left(x\right)dx, \\ dR_{Ice} = k_1\left(x\right)\rho_{Ice}\sqrt{rh}\,y\left(x\right)\left[\,f_{Id} - y'\left(x\right)\right]dx. \end{gathered} \tag{8}$$

($y(x)$ – equation for waterline). Elementary ice yawing moment can be calculated as follows:

$$dM = x\,dF - y\left(x\right)dR_{Ice} = k_1\left(x\right)\rho_{Ice}\sqrt{rh}\left\{x\,y\left(x\right) - y^2\left(x\right)\left[\,f_{Id} - y'\left(x\right)\right]\right\}dx. \tag{9}$$

The characteristics of the ship’s motion presented in horizontal plane will be affected only by additional ice forces, which appeared due to constriction of the space between two ships’ hulls by floes of broken ice. Concentration of ice floes between ships’ hulls differs from their concentration between outer side of hull and the border of the ice channel. It is obvious, that effect of these different forces is asymmetrical relative to the centre line; hence their action will cause the ice moment also.

Summary ice forces, affecting the hull when overtaking, can be expediently represented as the amount of forces acting in the compacted ice field (s = 10) and additional ice forces within ice channel filled by ice floes (s < 10):

$$R_{\Sigma Ice} = R_{Ice}\big|_{s=10} + R_{Ice}\big|_{s<10}; \quad F_{\Sigma} = F\big|_{s=10} + F\big|_{s<10}; \quad M_{\Sigma} = M\big|_{s=10} + M\big|_{s<10}. \tag{10}$$

Because $F\,|_{n\,=\,10} = 0$ and $M\,|_{n\,=\,10} = 0$ due to symmetry of the ice effects on ship hull relative to the center line, then

$$R_{\Sigma Ice} = R_{Ice}\big|_{s=10} + R_{Ice}\big|_{s<10}; \qquad F_{\Sigma} = F\big|_{s<10}; \qquad M_{\Sigma} = M\big|_{s<10}. \tag{11}$$

The scheme on Figure 4 describes that space constriction is observed only at a distance ζ from the starboard side of the ship. Then in accordance with the equation (11) total ice resistance of ship hull can be represented as sum of two components: resistance in infinity environment and additional resistance caused by space constriction.

Substituting form (4) into the first form of (11), it is possible finally get:

$$R_{Ice} = \int\limits_{\zeta(t)}^{0} q[n'(x)]\,\rho_{Ice}\sqrt{rh}\,y(x)[\,f_{ID} - y'(x)]dx. \tag{12}$$

Similarly, equations for additional side force and the yawing moment can be obtained in following forms:

$$F_{Ice} = \int\limits_{\zeta(t)}^{0} q[n'(x)]\,\rho_{Ice}\sqrt{rh}\,y(x)\,dx, \tag{13}$$

$$M_{Ice} = \int_{\zeta(t)}^{0} q[n'(x)]\rho_{Ice}\sqrt{rh}\,\{x\,y(x) - y^2(x)[\,f_{ID} - y'(x)]\}\,dx. \qquad (14)$$

Analytically geometry of the waterline - *y(x)* can be defined with using the following forms (Sazonov, 2006):

– for fore part of waterline

$$\begin{aligned} y_b &= \pm\frac{B}{2}, && x < 0.5L_{DF}, \\ y_b &= \pm\frac{B}{2}\left\{1 - \left[\frac{x - 0.5L_{DF}}{0.5(L - L_{DF})}\right]^{\frac{(L-L_{DF})\tan\alpha_0}{B}}\right\}, && 0.5L \ge x \ge 0.5L_{DF}. \end{aligned} \qquad (15)$$

– for aft part of waterline

$$\begin{aligned} y_s &= \pm\frac{B}{2}, && |x| < 0.5L_{DF}, \\ y_s &= \pm\frac{B}{2}\left\{1 - \left[\frac{-x - 0.5L_{DF}}{0.5(L - L_{DF})}\right]^{\frac{(L-L_{DF})\tan\alpha_{20}}{B}}\right\}, && 0.5L \ge |x| \ge 0.5L_{DF}. \end{aligned} \qquad (16)$$

In these and the following formulas the upper sign (±) corresponds to starboard side, the lower one corresponds to port side. Equations (15) and (16) are true in case if the maximum hull beam is on the midship frame. This description of the waterline differs from the usual one because it considers the dead flat (length – L_{DF}) as well as possibility of shifting the maximum hull beam from midship section of the hull.

Differentiation of equations (15) and (16) enables to determine allocation of the waterline inclination angle to the centerline along the hull length:

– for fore part of waterline

$$\begin{aligned} \alpha_b &= 0, && x < 0.5L_{DF}, \\ \alpha_b &= \mp\arctan\left\{\tan\alpha_0\left[\frac{x - 0.5L_{DF}}{0.5(L - L_{DF})}\right]^{\frac{(L-L_{DF})\tan\alpha_0}{B} - 1}\right\}, && 0.5L \ge x \ge 0.5L_{DF}. \end{aligned} \qquad (17)$$

– for aft part of waterline

$$\begin{aligned} \alpha_s &= 0, && |x| < 0.5L_{DF}, \\ \alpha_s &= \pm\arctan\left\{\tan\alpha_{20}\left[\frac{-x - 0.5L_{DF}}{0.5(L - L_{DF})}\right]^{\frac{(L-L_{DF})\tan\alpha_{20}}{B} - 1}\right\}, && 0.5L \ge |x| \ge 0.5L_{DF}. \end{aligned} \qquad (18)$$

The variable quantity - reciprocal value of relative width of the ice channel n' is determined in accordance with the scheme represented on Figure 4. Origin of axes axis of coordinates lies on the line that connects bow of the overtaking vessel and stern of the vessel overtaken. Then reciprocal relative width of ice channel can be calculated using the formula applied for overtaking vessel as function of time:

$$m(t) = \frac{y_2\left[0.5L_2 - x(t)\right]}{d - \left\{y_2\left[0.5L_2 - x(t)\right] + y_1\left[0.5L_1 + x(t) - z(t)\right]\right\}}. \tag{19}$$

Term of the overtaking process – T_{OT} is defined by the difference of overtaking vessel speed - V_2 and overtaken vessel speed - V_1 and their summarized length – L_1+L_2, that is

$$T_{OT} = \frac{L_1 + L_2}{V_2 - V_1}. \tag{20}$$

Variation time within range: $0 < t < T_{OT}$ permits to find values $x = (V_2 - V_1)\cdot t$ and then all values that are necessary to calculate the variation of the side force and yawing moment during process of overtaking.

This methodology was applied for development the mathematical model for calculation of the side force and yawing moment variation during process of the opposite motion of vessels within the ice channel.

RESULTS OF C0MPUTATIONS

For illustrating the capabilities and selfdescriptiveness of developed model the special computations were performed to look through the variation of side force and yawing moment and also ice resistance during process of overtaking.

Overtaking ship has following dimensions: length L_1 = 100 m, breadth B_1 = 30 m. Overtaken ship has dimensions: L_2 = 80 m, B_2 = 30 m. Velocity of overtaking: ΔV = 3 m/sec. Ice conditions were following: thickness h_{Ice} = 0.6 m, concentration s = 0.6.

Figure 5 presents variation of the side force F on the overtaking ship during passage along overtaken ship (solid line). For comparison, the variation of side force during same maneuver on the open water is presented by dotted curve. It is easy to see, that the direction of side force varies on opposite in the course of overtaking in ice conditions, while only the value of this force varies on open water. It is possible to explain as follows: the effective ice concentration between hulls of vessels sudden changes at passage of bow and stern of overtaking vessels by borders of cylindrical part of hull of overtaken vessel (s_1 or s_2 as compared with s_0, Figure 2).

Figure 6 presents variation of the yawing moment M on the overtaking ship during passage along overtaken ship. The character of variation of yawing moment is similar to moment for the open water and has more value.

These results correspond to model experiments in the main [Goncharov et al, 2009; 2009]. Experimental dependences $F(t)$ and $M(t)$ differ from calculated ones by presence of sign-variable spikes on curves. It is connected with the impact loads that large ice floes produce on the hull, when they are getting to space between hulls of vessels.

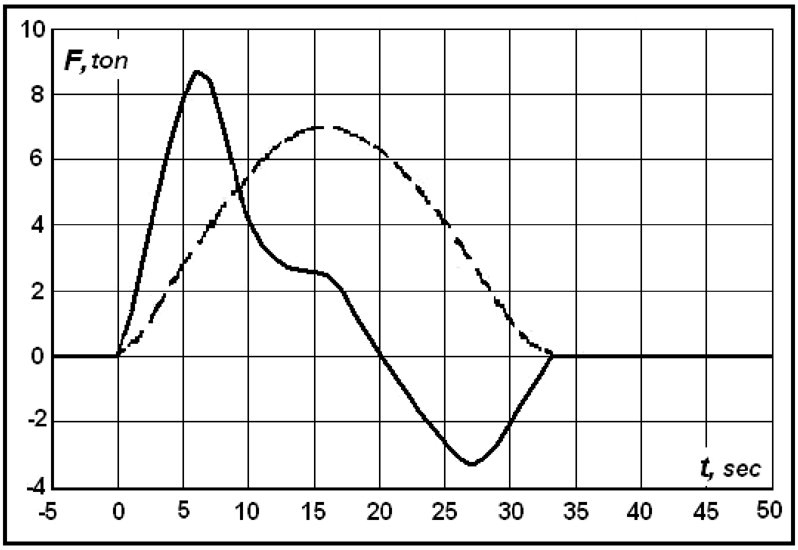

Figure 5. Variation of the side force *F* on the overtaking ship during passage along overtaken ship in ice conditions (solid line) and on open water (dotted line).

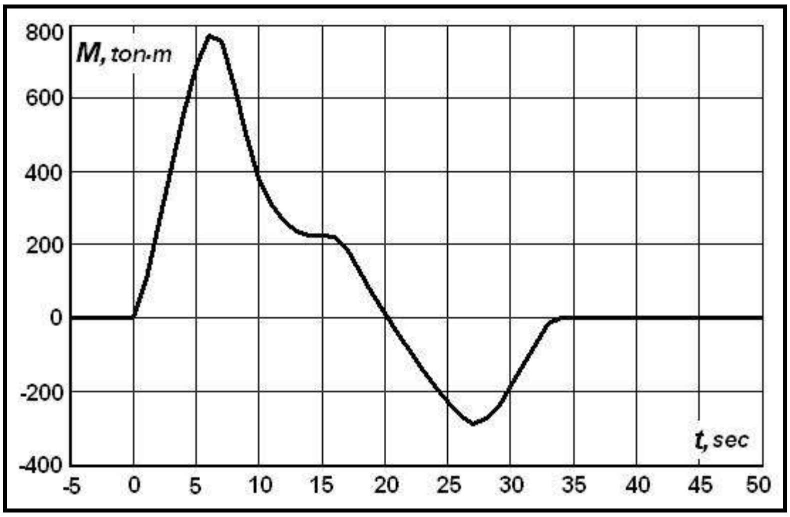

Figure 6. Variation of the yawing moment *M* on the overtaking ship during passage along overtaken ship.

Developed model gives possibilities to evaluate the variation of peak values of side force, ice resistance and yawing moment in dependence on minimal distance between vessels and the ice thickness, for example.

Figure 7*a* presents the dependence of peak values of side force *F* and ice resistance *R* on minimal beam distance between the vessels *d*, and Figure 7*b* presents similar dependence for yawing moment *M*. These data show that side force and yawing moment increase intensively under approaching of vessel in process of overtaking. These data give possibility to define the minimum allowable beam distance between vessels to provide safe maneuvering, if to set the extreme safe values of the side force or the yawing moment.

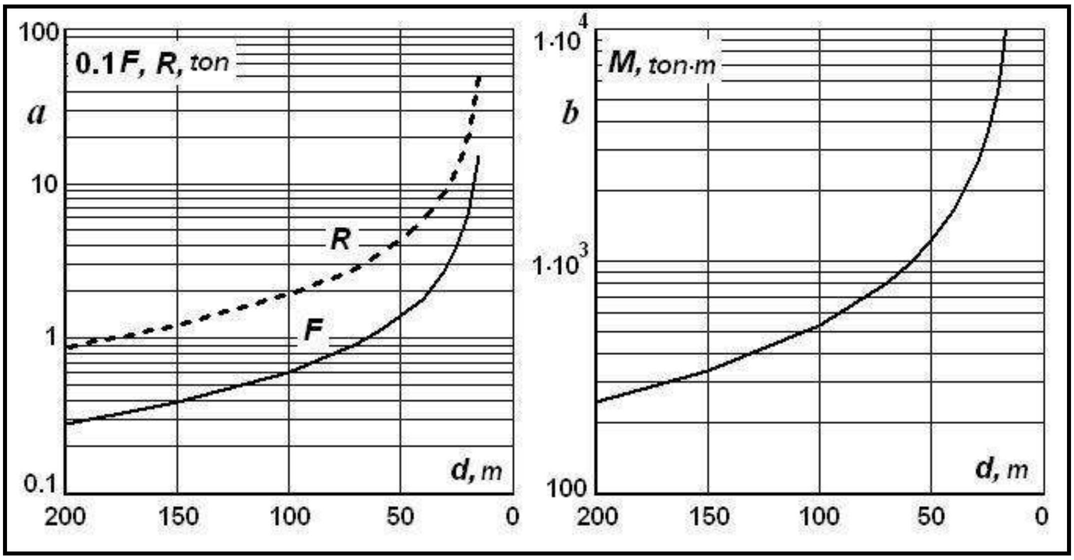

Figure 7. Dependence of peak values of side force *F* and ice resistance *R* (a) and yawing moment *M* on minimal beam distance between the vessels *d*.

Figure 8 illustrates the increase the side force *F* and ice resistance *R* under the ice thickness growth. These data correspond to expected dependence and confirm adequacy of developed model.

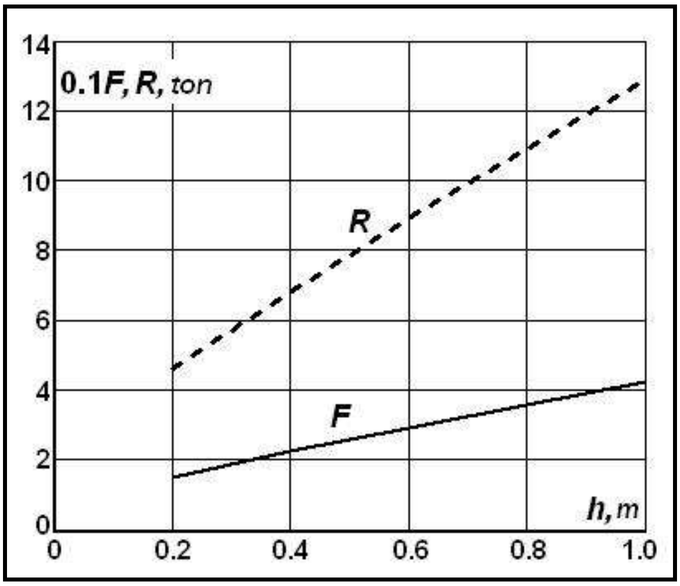

Figure 8. Increase the side force *F* and ice resistance *R* under the ice thickness growth.

CONCLUSION

Constructed mathematical model is closed one and gives possibility to calculate the side force and yawing moment, and ice resistance affecting on overtaking ship during passage along overtaken ship. It means that model can be applied to create special programs for simulators for training navigators to traffic within ice channel.

It is possible to apply model to define the safe regimes of maneuvering within the navigable ice channel in dependence on the ship dimensions, width of ice channel and ice conditions.

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