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MAKING A CHANNEL IN ICE FOR LARGE-SIZE SHIPS USING A CURVILINEAR ICEBREAKER PATH AND OTHER METHODS OVERVIEW

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ABSTRACT

Traditionally, the commercial vessels are sailing in ice through a channel made by an icebreaker. This tactics proved to be quite good for ships with hulls of lesser beam than that of the icebreaker they follow. Today there is an ever increasing demand for large-size carriers much wider than icebreakers. In this connection more efficient methods to assist these vessels through ice have to be developed.

The paper suggests a different tactical method when the icebreaker leading a large-size vessel is following a curvilinear path with a certain turning radius. This method makes it possible to reduce ice loads on the large-size vessel. This effect is achieved because the vessel partly drives through ice cake while passing directly through the channel made by the icebreaker, and also alternatingly one of the vessel hull sides breaks off small floes into the channel behind the icebreaker while the other hull side of the same vessel breaks the ice by bending.

The paper contains estimations of the icebreaker path, analysis and estimations of the vessel's ice resistance and speed in all phases of sailing through the water infested with small floes. The ice conditions suitable for this tactics are determined; the maximum safe speeds of the icebreaker and vessel are estimated to ensure fail-free operation.

The paper also reviews other existing icebreaker-assisted operation tactics for the cases when one ice-breaker leads a large-size vessel in continuous level ice fields. These tactics are analyzed to compare and appreciate the advantages of the curvilinear-path tactics.

MEANDERING ICEBREAKER TACTICS TO MAKE A CHANNEL IN ICE FOR A LARGE-SIZE SHIP

Traditional ice navigation tactics for commercial ships is to sail behind an icebreaker which is making a suitable navigation channel in ice for the ships. This tactics has proved successful for ships whose hull width is less than that of the icebreaker (Sazonov, 2010). However, today a popular trend is to operate large-size ships being much wider than existing icebreakers. In this connection there is a need to develop more efficient methods for ice navigation of commercial ships with assistance of existing icebreakers.

The tactical method suggested in this paper is a curvilinear (snake-like) pathway of the icebreaker sailing with a certain turning radius to lead a large-size ship through ice (Figure 1). Under these conditions the ice-breaking loads experienced by the ship led by a meandering icebreaker are less than in the case of straightforward icebreaker pathway when the ship sides have to crush ice edges of the channel made by the icebreaker. Following the suggested tactics the large-size ship under consideration will pass through small ice cake in the channel with her sides alternatingly chipping larger pieces of ice into the icebreaker's channel as well as breaking ice by bending on the other side, which is better in terms of ice resistance reduction than breaking ice by crushing.

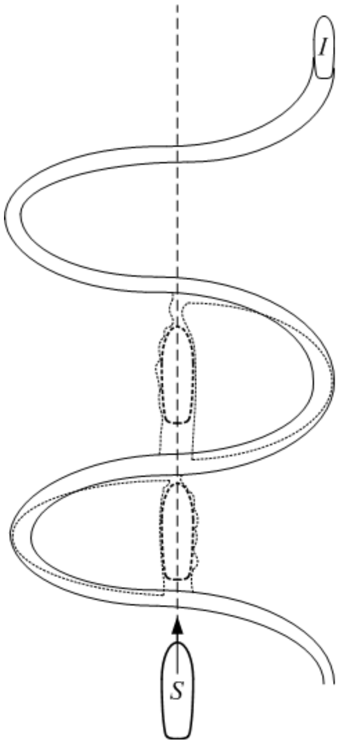


Figure 1. Scenario with one icebreaker

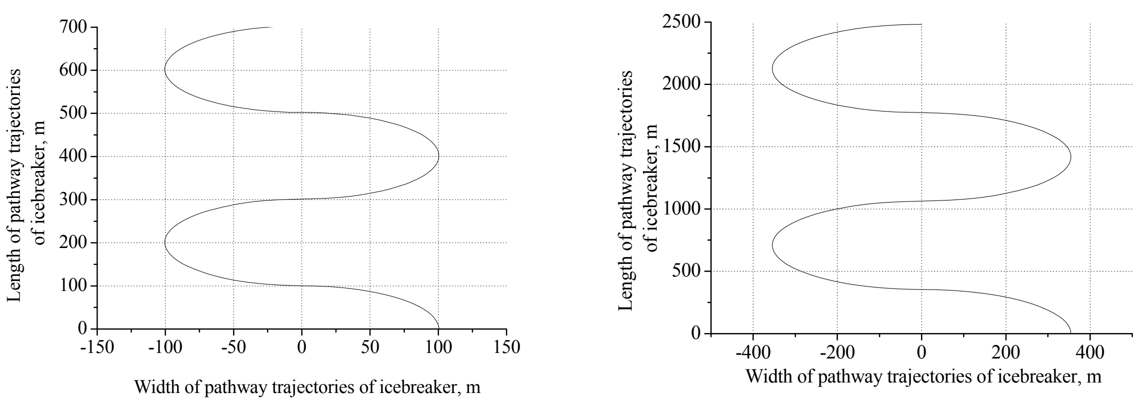
The efficiency of icebreaker in reducing ice loads on the escorted ship depends on the geometric characteristics of ice feature (ice thickness of level ice, height of ice ridge sail and depth of ice ridge keel), ice drift velocity and non-uniformity, icebreaker performance and maneuverability in ice. The geometric characteristics of ice features and icebreaker capabilities taken together determine the ship's operation profile in certain ice conditions.

Let us write the following mathematical equation to describe the curvilinear pathway of icebreaker leading a large-size ship through ice:

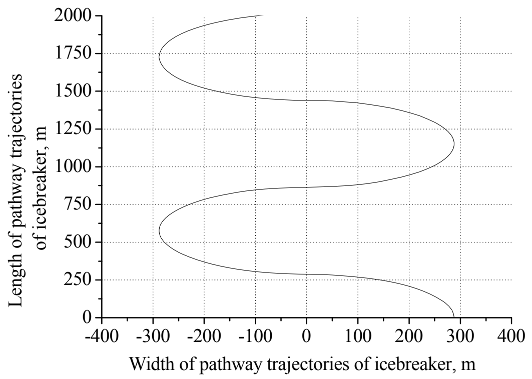
$$y_n = (-1)^n \cdot R \cdot \sqrt{1 - \frac{\left[x - (n+0{,}5)R\right]^2}{R}}, n = 0 \ldots k_n, \qquad (1)$$

where $R = \frac{D_w + kh_I^2}{2}$ – minimum turning radius, cables (D_w – diameter of icebreaker circulation, cable length; k – empirical coefficient k=2.7; h_I – ice thickness, m).

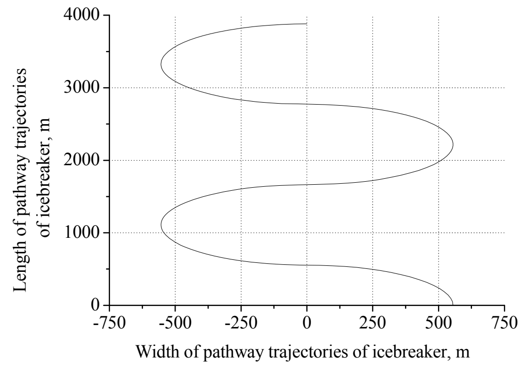
For the icebreakers propelled by modern propulsion pods with enhanced maneuverability the following relationship can be used $\frac{R}{L_I} = 2 \div 3$, where L_I – icebreaker length. Thus, for medium thickness ice we obtain the following pathway trajectories, see Figure 2.



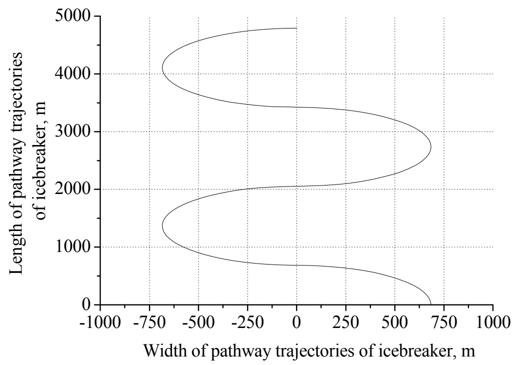
a) h=0.5m b) h=0.8m



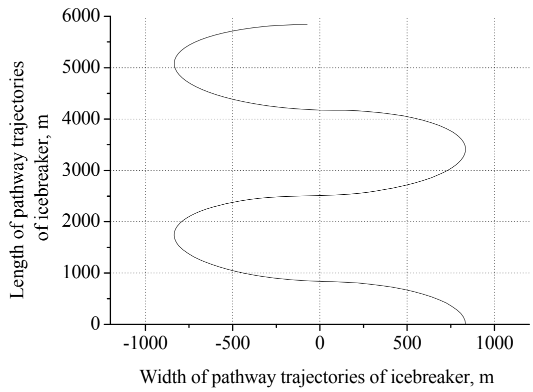
c) h=1m



d) h=1.2m



e) h=1.4m



f) h=1.6m

Figure 2. Icebreaker pathway in making a curved channel in different ice thickness h

Thus we obtain the pathway trajectories of icebreaker making a curved channel to lead a large-size ship through ice depending on ice thickness. The obtained trajectories make it possible to assess the size of floes which the large-size ship will have to pass in wake of icebreaker. Three trajectories are selected matching different ice thickness conditions for further analysis. Thus for 0.5m-thick ice the characteristic floe size is 200m, for 1m-thick ice it is 600m, and for 1.4m-thick ice this size is 1300m.

Ref. [5] (Sazonov, 2010) gives an estimate of ice feature sizes starting from the condition when it can be assumed that the ship is moving through continuous ice cover. In accordance with these estimates the characteristic length of ice feature is to be more than 1000 – 1500 m. From the obtained data on the floe sizes produced by meandering icebreaker it can be concluded that further consideration should be limited to ice thickness of not more than 1.5m because otherwise the floes will exceed 1500 m.

Table 1. Ship Main Data

Dimension	Large-size ship	Icebreaker
Length L_s, m	199.64	114.37
Beam B_s, m	39	27.5
Depth H_s, m	20.5	12.4
Draft T_s, m	11	8.5

The calculations should be started from estimations of the side force F produced by ship hull on an ice floe piece (Table 1). First, the ice resistance in a variable-width channel is determined. For this purpose the ice cutting coefficient of Yu.A. Shimansky (Kashtelyan & Poznyak et al., 1968) for different channel width is found. Only half-breadth B_s,of the ship is considered because only one ship side is in contact with the ice floe.

The next step required for finding the side force F is to calculate the ice resistance. The ice resistance is calculated for a range of ice thickness and ship speed values, also it is considered that in the process of ship and ice interaction the ice floe does not come into contact with the entire hull width. Ref. [4] (Ionov, 1988) provides a relationship for calculating the ship's total ice resistance.

The results of calculations are presented for large-size ship in Figures 3 – 4.

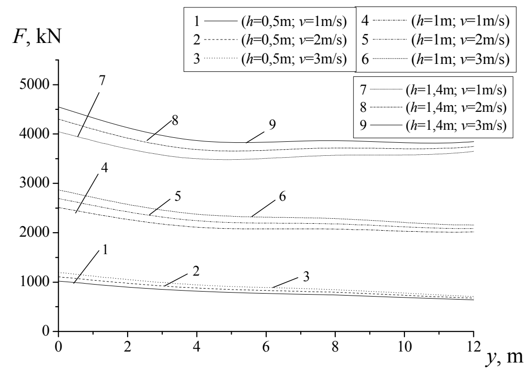


Figure 3. Side force on the ice floe from ship hull in function of ice channel width

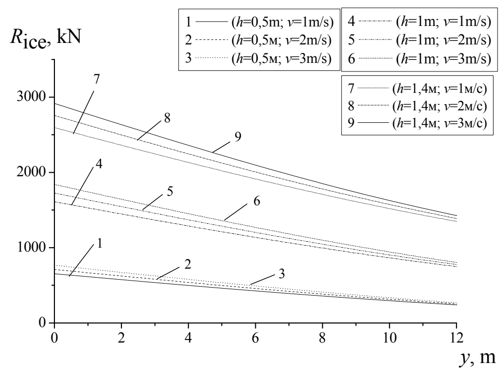


Figure 4. Ice resistance of large-size ship in function of ice channel width

The data on the side force and ice resistance versus ice channel, ice thickness and ship speed were thus approximated.

Next, the differential equation of motion for the ship pushing aside large pieces of broken ice was calculated:

$$\begin{cases}(1+k_{ship})M_{ship}\ddot{x} = T(x) - R_{ice}(\dot{x}, h, y)\\(1+k_{ice})M_{ice}\ddot{y} = F(\dot{x}, h, y) - P_w(\dot{y}^2)\end{cases} \quad (2)$$

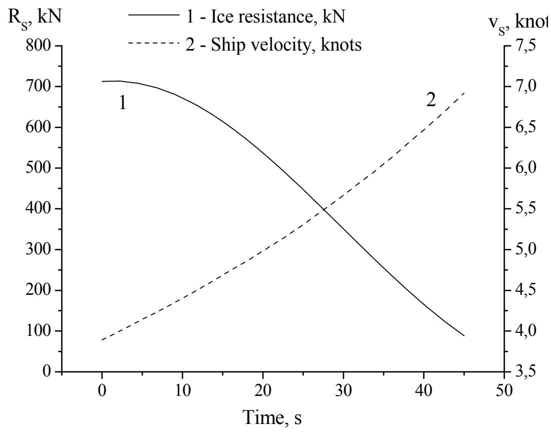
where M_{ice} - mass of ice floe piece; M_{ship} - mass of large-size ship, k_{ice} - ice floe added mass coefficient; k_{ship} - ship added mass coefficient; F - force on ice floe piece from ship hull; P_W - hydrodynamic resistance of ice floe piece (Sazonov, 2010); T – thrust of large-size ship.

In solving differential equation 4 we obtain the ice resistance versus time spent on penetration and pushing of the ice floe piece aside.

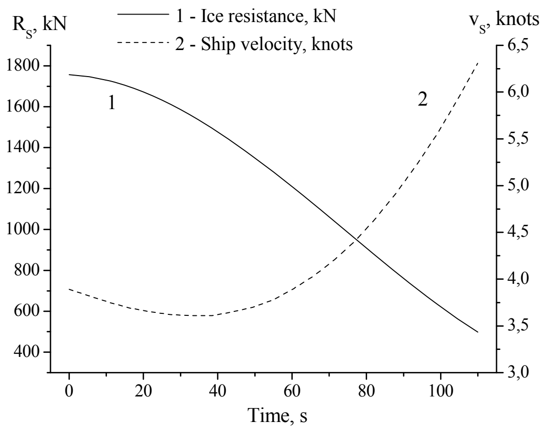
The analysis of results obtained from the calculations indicates that the icebreaker meandering tactics for escort of large-size ships is advisable in case of less than 1 m ice thickness. The curves of Figure 5 demonstrate that in 1.4m-thick ice the speed of large-size ship is notable reduced and finally the ship is jammed failing to push ice pieces aside. In 1m-thick ice the ship speed is also reduced as it penetrates an ice floe, but the speed reduction is not so drastic and the ship is able to gain the speed again when the ice resistance is reduced due to pushing of ice pieces and finally reach open water.

For the tactics under consideration it is also important to properly choose the speed of the icebreaker as well as the ship speed. Since the icebreaker is meandering the propulsion pod angle during turning is about 30 deg., while the large-size ship maintains the straight heading, it is obvious that the icebreaker speed should be higher to keep a safe distance between the vessels.

Based on the data available for the existing icebreakers with pod propulsion and enhanced maneuverability it is known that their average maximum speed (considering continuous turning maneuvers of these vessels) is around 4 kn in ice thickness of about 0.5m and around 2.5kn in ice thickness of about 1m (Sazonov, 2006). The pathway trajectories suggested for the icebreaker imply that the speed of large-size ship shall be half the speed of icebreaker to ensure a safe distance between the vessels all the time. Thus, in our case the maximum speed of large-size ship in 0.5m-thick ice is around 2kn, while in 1m-ice thickness it is around 1.2 kn.



a



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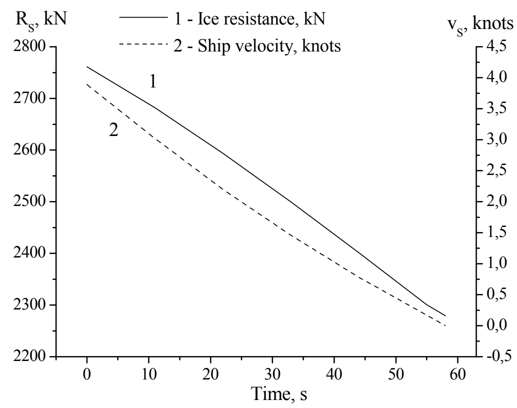

c

Figure 5. Ice resistance and ship speed in function of time taken by ship to push ice floe piece aside as well as initial speed of ship penetration into ice floe v_0=2 kn
a) ice thickness: 0.5m, characteristic size of ice piece: 200 m;
b) ice thickness: 1m, characteristic size of ice piece: 600 m;
c) ice thickness: 1.4м, characteristic size of ice piece: 1300 m.

There are also other methods that can be used in case of single-icebreaker assistance to large-size ships (Sazonov, 2006). One of the options is a three-step method (Figure 6). First, a channel of $L_{channel}$ length is made in level ice. In the second phase the icebreaker is running astern to make another channel parallel to the first channel. This second channel is designed to be combined with the first channel to provide a pathway of suitable width for the tanker in ice. In case of drifting ice when the pathway width is reduced the distance between these two parallel channels can be increased to compensate for the ice drift effects. Finally, in the third phase of these operations the icebreaker is running between the two parallel channels breaking in-between ice floes. Then this cycle is repeated.

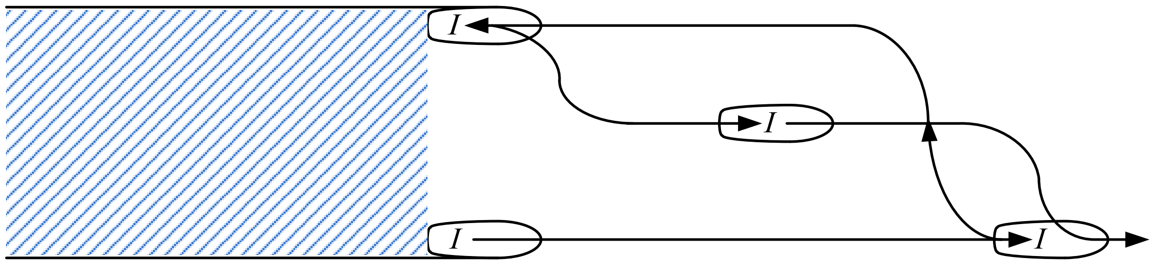

Figure 6. A schematic pathway of icebreaker making a wide navigation channel in ice

It should be noted that for minimizing the distance between the ship and icebreaker the assisted ship should start moving through the channel at the end of the third ice-breaking phase. This type of single icebreaker assistance tactics is likely to be advantageous in relatively light ice conditions with prevalently open water shipping lanes and small thickness of ice cover.

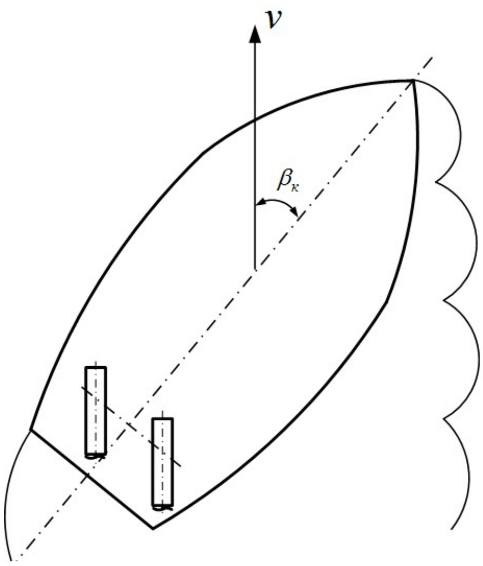

Figure 7 – Icebreaker with podded propulsion moving at drift angle

Another method of making a wide channel in ice for large-size ships is to use icebreakers with podded propulsion/steering systems (Mattson, 1998). In this case the icebreaker is running at a certain drift angle (Figure 7). This solution was worked out based on the developments of the Finnish engineers, viz. the use of an asymmetric hullform icebreaker for escort of large-size vessels. This asymmetric hull form allows the icebreaker to move in ice ahead as well as abeam. This mode of icebreaker operation is provided by three Azipods fitted at bow, stern and midship.

Ref. [2] (Sazonov, 2006) presents calculations of forces acting on the icebreaker operating in this mode. The analysis of the calculation results shows that that one icebreaker has limited capabilities for making a wide channel in ice when moving with a drift angle. In this mode the icebreaker is subject to very high side forces, which practically precludes this maneuver.

Also, for a common icebreaker, even if the propulsion system is able to generate sufficient thrust, it is expected that the motion with drift angle would be unstable. This conclusion is suggested by the fact that according to calculations the side ice force is almost ten times the longitudinal ice force. Under this situation any minor change in the environment conditions the icebreaker would tend to take the path of least resistance. Such instability of icebreaker's motion would result in a strongly curved pathway raising the probability of the escorted ship collisions with ragged edges of ice channel.

Therefore, the two last scenarios considered above are not regarded as efficient methods of making wide channels in ice by one icebreaker. With both methods the average speed of large-size ship operating in ice under icebreaker escort is significantly reduced. Nevertheless, the first of the above described scenarios, when the channel is made in three steps, could be recommended as a practical method only for the shipping routes with rather sparse ice-covered areas. The best ice navigation scenario for a large-size ship under escort of one or two icebreakers should finally be decided based on the analysis of economic efficiency for the specific operation under consideration.

In conclusion it should be noted that this paper is dealing with the scenario when a large-size ship is led in ice-covered waters by a meandering icebreaker. The possibility of reducing the ice resistance of a large-size ship led by a meandering icebreaker has been investigated. The single-icebreaker escort operations may be required in case of large-scale export of hydrocarbons from the Arctic fields, e.g. Yamal.

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