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Astern Running of Heavy-Tonnage Vessels in an Ice Channel

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Abstract

One of the most important tasks in raising the efficiency of marine transport systems is to make heavy-tonnage vessels move at faster speeds in channels laid by icebreakers. Studies conducted in the Krylov State Research Center (KSRC) Ice Basin have shown that broken ice is a significant factor that restricts vessel speed through ice channels. Wide breadths of heavy-tonnage vessels make it difficult to push ice pieces aside, resulting in their accumulation ahead of the bow. Ice blocks can be removed from the bow area only if they are immersed and passed along the hull underwater. With increasing speed, these processes require increasing amounts of energy. Possibly, easy ice passage along the underwater hull and speed improvements can be achieved if large-size vessels go stern first in ice channels. In this mode of operation, we have a number of factors contributing to the more efficient passage of ice provided by the small angle of the sternpost, making it easier for ice floes to dive under the hull, as well as the suction produced by the propellers. Moreover, the propeller slipstreams wash away the submerged ice outside the channel edges and reduce the ice friction of the underwater hull. This paper provides some theoretical assessments regarding the efficiency of running a large-sized vessel astern in an ice channel. Model studies have been undertaken in the KSRC Ice Basin to confirm that the suggested mode of operation is effective. During these experiments, models of large vessels were run through an ice channel to determine their ice resistance and speed. The theoretical estimates were compared with the model test results obtained for the Ice Basin. The analysis of all results proves that the described mode of operation promises faster vessels through ice channels.

Keywords: Heavy-tonnage vessel, Propulsion in ice, Hull form, Ice basin, Model tests

1. Introduction

Shipping in the Arctic region and freezing seas play an important role in economics. The XXI century saw substantial changes in the methods of marine operations under ice conditions, primarily related to a wider application of heavy-tonnage vessels. Unlike previously used vessels in the Arctic, modern ships have larger principal dimensions (beam, length, displacement), which make traditional icebreaker practice not very suitable for leading these vessels on ice. The breadth of modern large vessels is much greater than that of any existing icebreaker. For this reason, the vessel running behind the icebreaker has to complete ice breaking and widen the channel [1,2]. This effort requires substantial power from the propulsion plant and gives rise to new effects that affect ship motion in a narrow ice channel. One of these effects is the asymmetric ship motion with respect to the channel's central axis due to the interaction between the hull and the channel edges [3].

When a heavy-tonnage vessel moves through an ice channel laid by an icebreaker, there is also a higher resistance of broken ice. This effect is due to two factors. The first factor arises in connection with channel edges, making it difficult for the hull to push aside small ice pieces, as is well known [4]. The second factor is the bow shape of the heavy-tonnage vessels, which is less suitable for pushing ice floes aside than conventional ice-class vessels. This generates an area of broken ice, which is towed by the ship, thus increasing its ice resistance. The ship moving ahead in an ice channel was considered by the Sazonov and Dobrodeev [5]. It should be noted that at faster speeds in the ice channel, the resistance of broken ice to heavy-tonnage vessels is increased according to experimental results [6].

At present, one of the critical tasks addressed by Arctic navigators is to increase the average speed of heavy-tonnage vessels in ice [6,7]. Certain problems are encountered when

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ships run in channels made of ice more than 1.5 m thick. Therefore, the analysis of various tactical methods that can potentially increase the average speed of heavy-tonnage vessels could be of interest.

This paper considers the advantages and disadvantages of running heavy-tonnage vessels astern in an ice channel. The considerations herein primarily refer to ships equipped with propulsion pods, but are also applicable to vessels with a traditional arrangement of propellers and rudders.

2. Experimental Facility

Studies regarding the astern operation of commercial vessels in ice channels filled with broken ice were carried out based on model test data obtained in the Ice Basin of Krylov State Research Center (KSRC). KSRC Ice Basin has the following dimensions: test section length: 80 m, width: 10 m, depth: 2.0 m. For experiments the fine-grained (FG-type) ice was frozen [8]. Ice resistance experiments were carried out by towing tests of ship models with running propellers according to the International Towing Tank Conference (ITTC) Guidelines [9].

In compliance with the ITTC Guidance [8], a channel packed with broken ice was modeled by freezing solid-level ice followed by forming the ice channel. The ice channel width was chosen to be 10% wider than the tested breadth of the ship. The ice pieces in the channel were mainly square, measuring from 5 to 8 m in length. Such ice fragments are classified as an ice cake typical of channels cut into solid-level ice. The ice concentration in the channel was 9/10 (Figure 1).

3. Ship Models

Ice resistance studies were conducted for five ice-class carriers equipped with propulsion and steering pods. The ships have different dimensions, purposes, hull forms, and numbers of thrusters. The main aspects are summarized in Table 1.

Figure 1. Model ice channel filled with broken ice (concentration 9/10)

The most important hull-form parameters for ice-resistance estimates are frame angles β, stem and sternpost angles ϕ_b and ϕ_c, respectively, and the angle of waterline α (Figure 2).

The waterline slope angle α is measured at the buttock attachment point at a B/4 distance from the centerline plane. The angles of stem γ_b and sternpost γ_c are measured in the centerline plane. All vessels under consideration have a stern skeg in the centerline plane. It should be noted that ship no. 3 has a pronounced forefoot to accommodate transverse thrusters. Table 1 lists the main characteristics of the ships tested in the Ice Basin.

4. Model Tests

Model tests were conducted under different ice conditions, which were chosen by taking into consideration each vessel's ice-going capabilities, operation areas, and propulsion power requirements. To analyze the efficiency of the stern-first operation, experiments were conducted on models running both astern and ahead on ice of equal thickness at the same speeds. The proposed approach enables the comparison of the ship ice resistance in ice channels under astern and ahead running conditions.

Movement in an ice channel is one of the most common modes of transport vessel navigation under ice conditions. It ensures efficient operation at high speed. At the same time, the risk of damage to the propellers and projections increases [10]. Therefore, studies of the hull interaction with broken ice in an ice basin are model tests for specification design.

Table 2 lists the characteristics of the ice and ship speeds modeled in the Ice Basin.

Figures 3-7 below show pictures illustrating the main episodes of the model tests in an ice channel filled with broken ice.

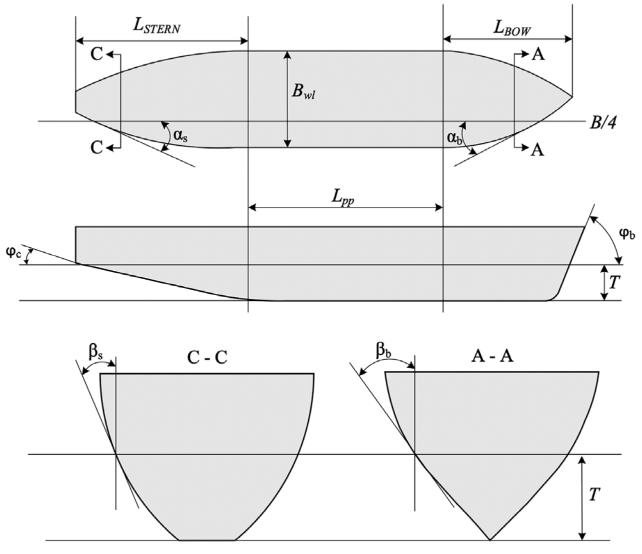


Figure 2. Definition of the angles of the hull elements

Table 1. *Main specifications of the ships*

Description	Symbol	Ship 1	Ship 2	Ship 3	Ship 4	Ship 5
Number of pods	1	2	3	2	3	3
Model scale	λ	1:20	1:34.4	1:22.5	1:34.4	1:33.3
Length between perpendiculars	L_{pp}, m	114.0	280.0	109.0	285.0	284.0
Waterline breadth	B_{wl}, m	24.0	49.0	25.0	47.0	42.0
Length of entrance	L_{BOW}, m	38.0	95.0	33.0	72.0	58.0
Length of run	L_{STERN}, m	23.0	77.0	22.0	58.0	41.0
Drafts at midships	T, m	7.0	12.0	8.0	12.0	12.0
Displacement	D, m^3	14 000	135 000	13 000	126 000	100 000
Angle of the stem	ϕ_b, degree	60	23	20	25	32
Angle of the sternpost	ϕ_c, degree	47	22	34	22	20
Waterline run slope at B/4 distance	α_b, degree	33	52	35	48	44
Waterline entrance slope at B/4 distance	α_s, degree	55	46	60	43	55
Frame angle and bow	β_b, degree	-	-	-	-	-
at $0.5 \cdot B_{wl}$	$\beta_{b-0,5}$, degree	28	80	75	72	60
at $0.4 \cdot B_{wl}$	$\beta_{b-0,4}$, degree	25	71	67	69	52
at $0.3 \cdot B_{wl}$	$\beta_{b-0,3}$, degree	22	60	60	65	50
at $0.2 \cdot B_{wl}$	$\beta_{b-0,2}$, degree	12	53	45	57	44
at $0.1 \cdot B_{wl}$	$\beta_{b-0,1}$, degree	7	44	30	46	30
Frame angle, stern	β_s, degree	-	-	-	-	-
at $0.5 \cdot B_{wl}$	$\beta_{s-0,5}$, degree	86	75	80	78	80
at $0.4 \cdot B_{wl}$	$\beta_{s-0,4}$, degree	82	67	76	74	77
at $0.3 \cdot B_{wl}$	$\beta_{s-0,3}$, degree	77	65	71	70	74
at $0.2 \cdot B_{wl}$	$\beta_{s-0,2}$, degree	64	63	58	68	70
at $0.1 \cdot B_{wl}$	$\beta_{s-0,1}$, degree	52	51	35	54	58

5. Model Testing Data

The model test data are shown as the relative ice resistance $R_{I\ Ahead}/R_{I\ Astern}$, (where $R_{I\ Astern}$ - ice resistance of model's running astern at a given speed, $R_{I\ Ahead}$ - ice resistance of model's running ahead at the same speed) as a function of Froude number with respect to ice thickness $Fr_h = v/\sqrt{gH}$ (Figure 8).

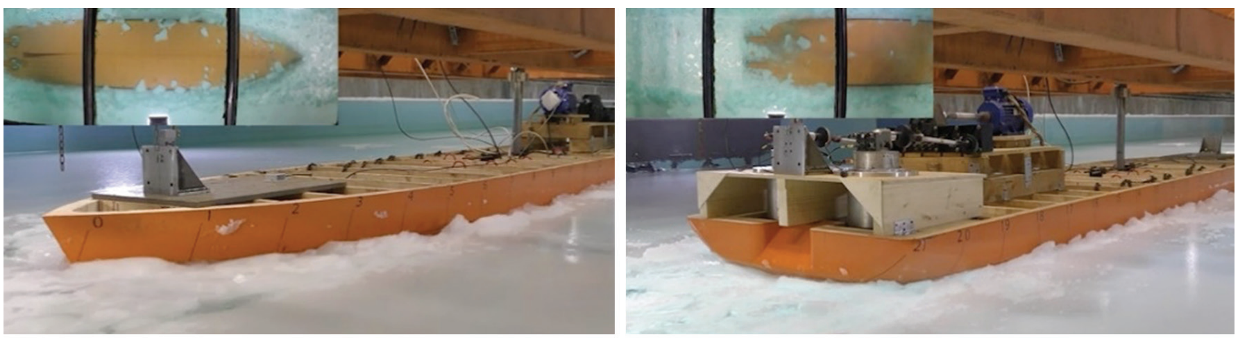
The obtained results provide conclusive evidence that four out of five ships go more efficiently through the ice channel in the astern running mode than in the ahead running mode. The highest efficiency was achieved for ship no. 3 because the forefoot caused additional ice resistance in the ahead running mode. Figure 7 intensive interaction of the forefoot with ice. While in astern running mode, the forefoot of a similar design is not exposed to the ice effect as strongly as that because it is washed with propeller slipstreams.

Practically the same results were obtained for ships 2 and 4 as they have similar hull forms in terms of the main criteria and absolutely identical test conditions and full-scale correlation. These are heavy-tonnage vessels with icebreaker bow and stern lines. It should be noted that the bow concept of these vessels differs. Ship no. 2 had a spoon-type bow, while ship no. 4 had a wedge-type bow. However, the angles of the stem, waterline, and frames at the standard measurement points are quite similar. Obviously, different bow concepts have little influence on ships moving in a fresh ice channel if their other hull form characteristics are somewhat similar. The test data show that the level of ice resistance in astern mode for both ship types was reduced by 15-20%.

Ship no. 1 is slightly more effective in reducing ice resistance than large-size vessels with an icebreaker's hull form. This ship has a low block coefficient and a slender bow, giving her advantages for sailing through broken ice because this vessel is capable of pushing ice cake aside. However, these effects were observed only at low ice concentrations below 6/10 and in open water. All experiments in the ice basin were performed in an ice channel of limited width with an ice concentration

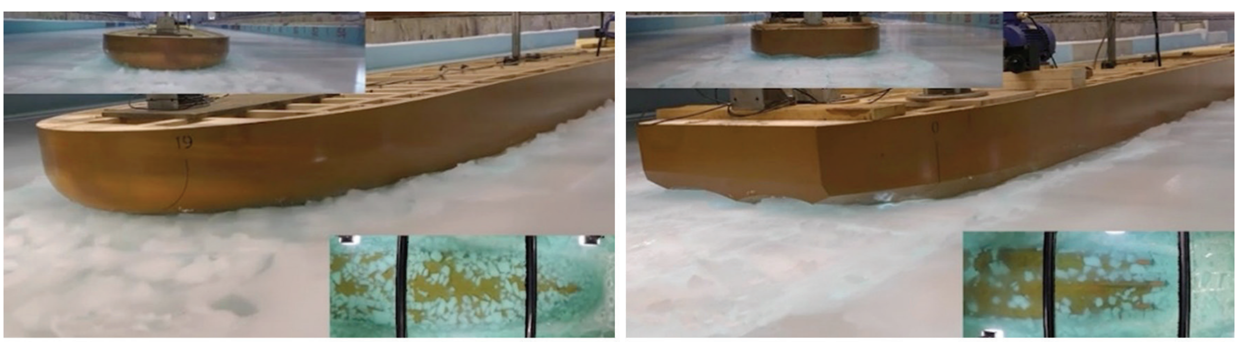
Table 2. *Test conditions*

Description	Symbol	Ship 1	Ship 2	Ship 3	Ship 4	Ship 5
Ice thickness A	H_A, m	0.6	1.5	1.5	1.5	1.2
Speed A1	V_{SA1}, knots	8.0	11.0	8.0	11.0	12.0
Speed A2	V_{SA2}, knots	6.0	9.0	6.0	9.0	9.0
Speed A3	V_{SA3}, knots	4.0	7.0	4.0	7.0	6.0
Speed A4	V_{SA4}, knots	-	-	-	-	4.0
Ice thickness B	H_B, m	0.9	2.1	2.0	2.1	1.7
Speed B1	V_{SB1}, knots	8.0	9.0	6.0	9.0	12.0
Speed B2	V_{SB2}, knots	6.0	7.0	4.0	7.0	9.0
Speed B3	V_{SB3}, knots	4.0	5.0	2.0	5.0	6.0
Speed B4	V_{SB4}, knots	-	-	-	-	4.0



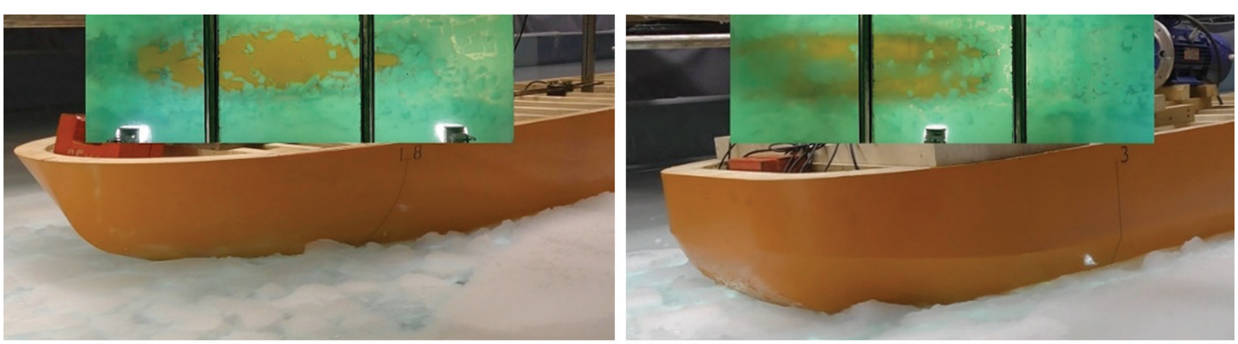
a) Running ahead: *b) Running the astern*

Figure 3. *Model tests of ship 1*



a) Running ahead: *b) Running the astern*

Figure 4. *Model tests of ship 2*

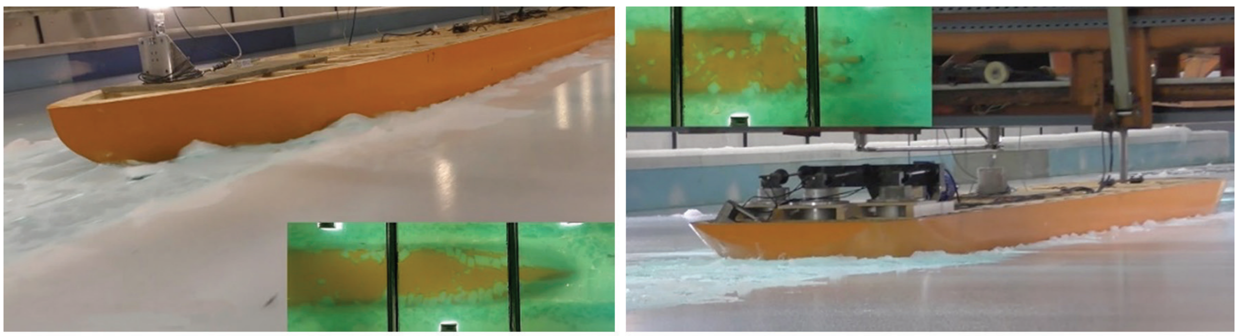


a) Running ahead: *b) Running the astern*

Figure 5. *Model tests of ship 3*

a) Running ahead: *b) Running the astern*

Figure 6. *Model tests of ship 4*



a) Running ahead: *b) Running the astern*

Figure 7. *Model tests of ship 5*

of 9/10. When concentrated ice is brushed aside by stems, an ice crushing effect occurs in the pathway of the transition from entrance to parallel middle body. Thus, the icebreaker's stern also provides vessel advantages in astern mode.

The relationship between ship resistance and speed is of some interest. The linear trends seen in the test data in Figure 8 show that vessels with a forefoot and spoon bow tend to have more ice resistance in ahead running mode than in astern running mode. For ships with a more slender bow, the trend was reversed. It was indicated above that the test data for ships no. 2 and no. 4 was practically the same. However, it is expected that at faster speeds, the difference between these two vessels will become more vivid.

According to the model test results, ship no. 5 has a 5-10% reduction in ice resistance when moving ahead. Differing from other results, this outcome has established an important criterion that may have a significant impact on better ship ice propulsion under astern running conditions compared to ahead running conditions. This criterion is the hull form. Ship no. 5 had a shorter aft entrance, which was 1.5 times smaller than that of ships no. 2 and 4, which had similar dimensions. In this case, the distance from the waterline to the propulsion pod struts is considerably reduced, which prevents ice pieces submerged by the hull from being arranged in such a way as to have the least influence on the struts of the ship control surfaces. The effects obtained are described in detail in Lee's [11] study. Also, the reduction in ice resistance when running ahead can be explained by a somewhat different bow shape from that of ships no. 2 and 4. In this case, the ship has a clear wedge-shaped hull and lower frame angles, which promotes the submergence of ice by the hull and also exerts an additional lateral force to throw ice under the ice

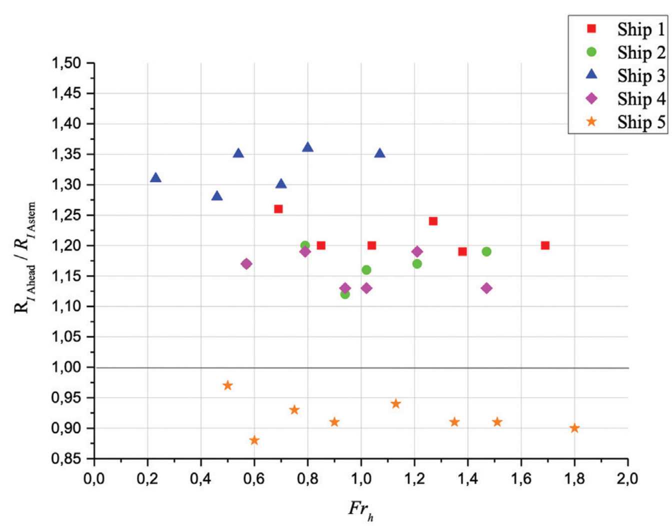


Figure 8. *Relative ice resistance as a function of Froude number with respect to ice thickness*

channel edge. Thus, the resistance component depending on the ice friction against the hull plating is reduced because the underwater hull is cleared of broken ice.

6. Discussion of Results

Let us consider in more detail the physical processes that may reduce ice resistance during astern running of a heavy-tonnage vessel under ice conditions, including ice channels filled with broken ice. Commonly, three groups of factors that may lead to the reduction of ice resistance are distinguished. First, it is the hull form of a heavy-tonnage vessel, which, as a rule, features a lower angle of the sternpost than the stem angle. Second, the propeller suction changes the flow pattern. The propeller suction is associated with the thrust deduction arising from the hull of the ship moving ahead in open water. Third, it was washed by propeller slipstreams. Let us make some assessments of these factors on the ice resistance of a heavy-tonnage vessel moving through an ice channel.

The angle between the stem and sternpost, under all other conditions being equal (ship speed and thickness of broken ice are constant), only influences the diving of ice pieces under the hull.

The elementary consideration of ice pieces sliding on an inclined plane without taking into account friction forces gives the following relation:

$$tg\varphi \leq \frac{R_w(V)}{h_I S_{If}(\rho_w - \rho_I)}, \quad (1)$$

where φ - angle of stem of sternpost; $R_w(V) = C_w \frac{\rho_w V^2}{2} S_{Ic}$ - resistance of water at the ice floe being towed by the bow or stern of the ship running in channel; C_w - resistance coefficient of the ice floe being towed; V is the ship speed; $S_{Ic} \approx B\,l_{Ic}$ - area of the ice feature in front of the bow or stern; B - ship beam; ρ_w, ρ_I - density of water or ice, respectively; $S_{If} \approx B\,l_{If}$ - area of the ice layer submerged by the bow or stern; l_{If} - length of the ice layer equal to the length of individual ice floes.

The obtained relation makes it possible to determine the influence of the stem and sternpost angles on the ice resistance at constant ship speed and ice thickness. In this case, the function can be rewritten as follows:

$$tg\varphi \leq K\frac{l_{Ic}}{l_{If}}, \quad K = \frac{C_w V^2}{2h_I\left(1 - \frac{\rho_I}{\rho_w}\right)}. \quad (2)$$

With this formula, it can be shown, for instance, that the length of accumulated ice in front of the 22º bow will be less than that in front of the 18º sternpost $l_{Ic}(22) \approx 1.24\,l_{Ic}(18)$. In this case, the floe lengths are assumed to be the same.

The influence of propeller operation on the flow pattern around has been thoroughly studied in Ignatev's study [12] concerning the application of bow propellers in icebreakers. Below, we quote some results drawn from this investigation. The graphs given below show the relative longitudinal velocity $k_x = \frac{V}{w_a}$, (Figure 9) and the pressure coefficient in induced flow $\xi = \frac{p}{\rho_w w_a^2}$ (Figure 10), where $w_a = V(\sqrt{1+\sigma_p} - 1)$ - total induced velocity in the propeller jet at infinity; $\sigma_p = \frac{2T}{\rho_w V^2 F}$ - thrust load coefficient; T - propeller thrust; F - area of the propeller hydraulic section; p - fluid pressure taking account of the atmospheric pressure. In the graphs, the origin of the axes coincides with the propeller location, X-axis is positive in the ship's motion direction, the Y-axis is positive upward, and r is a polar coordinate with respect to the propeller axis.

Figure 9 shows the relative longitudinal velocity for an unlimited flow. The ice cover values on the graph should be multiplied by 2.

From the calculation results presented here, it follows that the longitudinal force has only a local effect of increasing velocity near the propeller, which is more favorable for ice pieces that

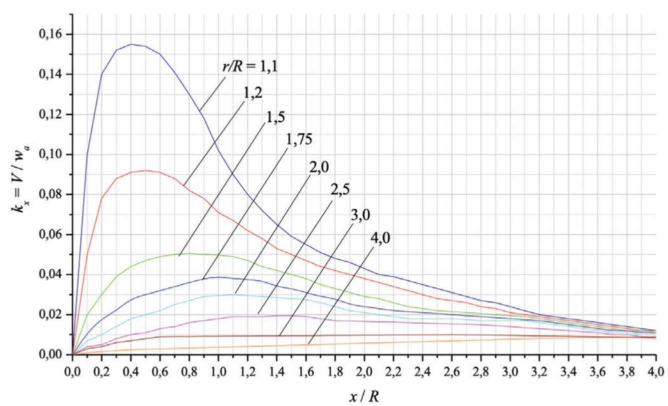


Figure 9. Values of the propeller-induced longitudinal force

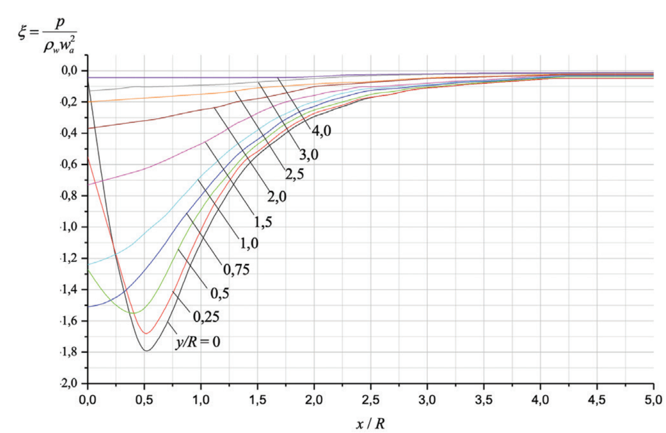


Figure 10. *Pressure coefficient* $\xi = f\left(\frac{x}{R}, \frac{y}{R}\right)$ *for h = 1.2R at propeller operation under an ice cover*

are diving under the hull. The negative pressure produced by the propeller is small and cannot affect the diving of ice pieces in any noticeable way; however, it promotes this process.

Obviously, the effects associated with propeller-induced velocities and propeller suction strongly depend on the stern lines and design characteristics of a heavy-tonnage ice-class vessel. Nevertheless, a positive influence on the stern-broken ice interaction in the channel, as described above, will remain.

For a ship running astern in a channel, an important role is played by washing the hull with propeller slipstreams. It is difficult to assess the influence of this effect. However, our visual observations of the models in the Ice Basin strongly confirm this assumption. Figures 3-7 show photos of the underwater hulls investigated during these Ice Basin model experiments of heavy-tonnage vessels moving astern and ahead in the ice channel, illustrating this conclusion.

7. Conclusion

Studies based on calculations and experiments have proven that heavy-tonnage vessels can effectively run asterns in ice channels filled with broken ice. According to the model test data obtained for a series of heavy-tonnage vessels in the Ice Basin, three groups of factors promoting the reduction of ice resistance can be identified: vessel stern lines, propeller suction, and hull washing by propeller slipstreams. The theoretical appraisals of these factors on the ice resistance of heavy-tonnage vessels in ice channels were fully validated by the Ice Basin model test data, which also provided additional insight into the effects associated with propeller suction on ships in astern running mode.

Footnotes

Authorship Contributions

Concept design: A. Dobrodeev, Data Collection or Processing: A. Dobrodeev, Analysis or Interpretation: K. Sazonov, Literature Review: K. Sazonov, Writing, Reviewing and Editing: A. Dobrodeev, and K. Sazonov.

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