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Features of an ice interaction with hull and propulsion system for a large-size vessels moving astern

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ABSTRACT

The efficiency of a ship to move astern in ice conditions is considered as one of the criteria to assess the hull form in the design process. Evaluation of ice going performance in this mode is a mandatory condition for the designer of a high ice-class vessel. The best performance in sailing astern is reached not only due to a well-known effect of propeller slipstream around hull but also by optimum shaping of the stern too. In view of the high propulsion requirements in ice environment there is a need to preliminary estimate the ice resistance for astern conditions early in the design process. However, the lack of generally accepted methods for ice resistance calculations make it a rather challenging task.

This paper presents some studies on interaction of the hull and propeller/rudder system with ice in case of a heavy-tonnage ship sailing astern. Theoretical estimates related to astern sailing in level ice are given. Mechanisms of ice breaking are considered for various types of stern shapes: a conventional shape adapted to common propellers in bossing and a shape intended for podded propulsion. Analysis of stern/level ice interaction is carried out, and the influence of propeller revolutions on the ice resistance in model ice-basin tests is assessed.

Prediction of ice propulsion of ships and ship convoys in astern sailing conditions will complement the existing techniques for assessing ice-going capabilities of ships sailing ahead. It helps to enable proper evaluation of marine transportation system's efficiency and planning of icebreakers and cargo carriers operations. The obtained data can also be used to elaborate ice-propulsion requirements for icebreakers and heavy-tonnage ice-going vessels.

KEY WORDS: Astern moving; Heavy-tonnage vessel; Ice performance; Ice resistance; Podded propulsion.

INTRODUCTION

Successful voyages of heavy-tonnage YamalMax vessels without icebreaker support via Northern Sea Route are growing from year to year. It is planned to increase the number of Arctic LNG tankers and optimize their hull form for efficient operation in the eastern Arctic sector, making this mode of shipping one of the main kinds of transportation. For passing the most difficult parts, like Taimyr and Aionsky ice massifs, navigators resort to astern sailing tactics. Moving stern first is the main feature of double-acting tankers (Juurmaa et al., 2001; Shtrek, 2013) started to be actively developed several decades ago (Backstrom et al., 1995). This concept was based on well-known facts of increased ice-going capability in astern mode (Ignat'ev, 1966).

While the astern sailing becomes an important aspect of the efficient operation in ice, it is vital to develop mathematical models for stern/solid ice interaction. Analysis of literature has shown that propulsion estimations for ships sailing astern in ice omitted and ignored the aspects of stern interaction with solid ice (Su et al., 2014). Propulsion astern was practically calculated as it was done for sailing ahead (Su et al., 2010).

Observations performed at Krylov State Research Centre (Denisov et al., 2015) reveal at least two features of astern sailing making it different from sailing ahead. These are ice breaking patterns by stern and influence of propellers on ice resistance of astern moving vessel. The paper studies these aspects.

STERN TYPES OF ICE-GOING SHIPS UNDER CONSIDERATION

Modern icebreakers and ice-going ships have two types of sterns:

- conventional stern adapted for common propellers in bossing (Figure 1a),

b)

a) c)

Figure 1 – Conventional icebreaker stern (*a*) and stern intended for podded propellers (*b*)

- stern adapted for podded propulsion (Lopashev, 2017), which are subdivided into:
  - ✓ traditional arrangement of podded propellers whose number depends on the ships propulsion power and main dimensions (Figure 1b);
  - ✓ hybrid arrangement, which consists of common propeller in bossing and podded propellers (Figure 1c). The number of each propeller type is determined in the ship design process and depends on her mission.

The conventional stern has a wedge-like form, like bow, and the ice breaking pattern by stern is practically the same as by bow. Therefore, the ice resistance in case of breaking by stern can be calculated by common methods (Lindqvist, 1989, Ionov, 2001).

The stern adapted to podded propellers has features different from the traditional stern. This stern is a cantilever structure with a pronounced overhang. The overhang has a rather large flat part (sometimes it may have a small deadrise, i.e. angle of bottom inclination to sides) with openings for podded propellers. The size of flat part should provide a 360° rotation of propeller pod. With podded propellers the hull form features full afterbody waterlines with entrance close to 90°. The fullness of afterbody waterlines is explained by the need to constrain the rotation of pods within the running waterline.

Ice horns are often installed in the aft, behind podded propellers, with intention to protect the pod strut from direct ice interaction when moving astern. An ice horn is also often fitted in the longitudinal centerplane even when there is no podded propeller there. This horn is designed to break large pieces of ice, which may form between the pods.

It should be mentioned that the ship sterns with only one podded propeller is in-between the sterns for traditional propellers and those adapted to arrange two or more pods.

ICE BREAKING PATTERNS BY STERN

Studies of ice breaking patterns by sterns of model icebreakers and vessels equipped with several podded propellers have shown that the size and shape of formed ice pieces are different from those observed when ice is broken by traditional sterns. The main difference lies in that: when a wide stern interacts with ice cover, large pieces of ice may form, their width being comparable with 1/3 afterbody waterline. Model tests were performed in the ice basin of Krylov State Research Centre for various types of vessels equipped with podded propellers and propellers in bossings. Figure 2 views sterns of various ship models and ice breaking patterns by their hulls.

Experiments were conducted astern in simulated ice of FG type. The fine-grained ice is accreted upwards by laminating layers of fine-grained ice over the water surface in an ice tank. This technology enables ice basins to increase their ice test productivity. The thickness of level ice and its flexural strength were 1.0 m and 500 kPa, respectively, as calculated for full-scale conditions. All ship models were equipped with rudder/propeller systems, which made it possible to conduct towed propulsion tests in line with ITTC Guidelines No.7.5–02.04-02.2. The speed of models was about 3.0 knots. The number of propeller revolutions was chosen under bollard pull conditions and corresponded to ship horsepower of 100%.

Model tests of ships equipped with podded propulsion were performed for three absolutely different concepts:

- tanker equipped with 3 podded propellers (Figure 2b). Let us assume that the main dimensions: length – L; breadth – B, draught – T;

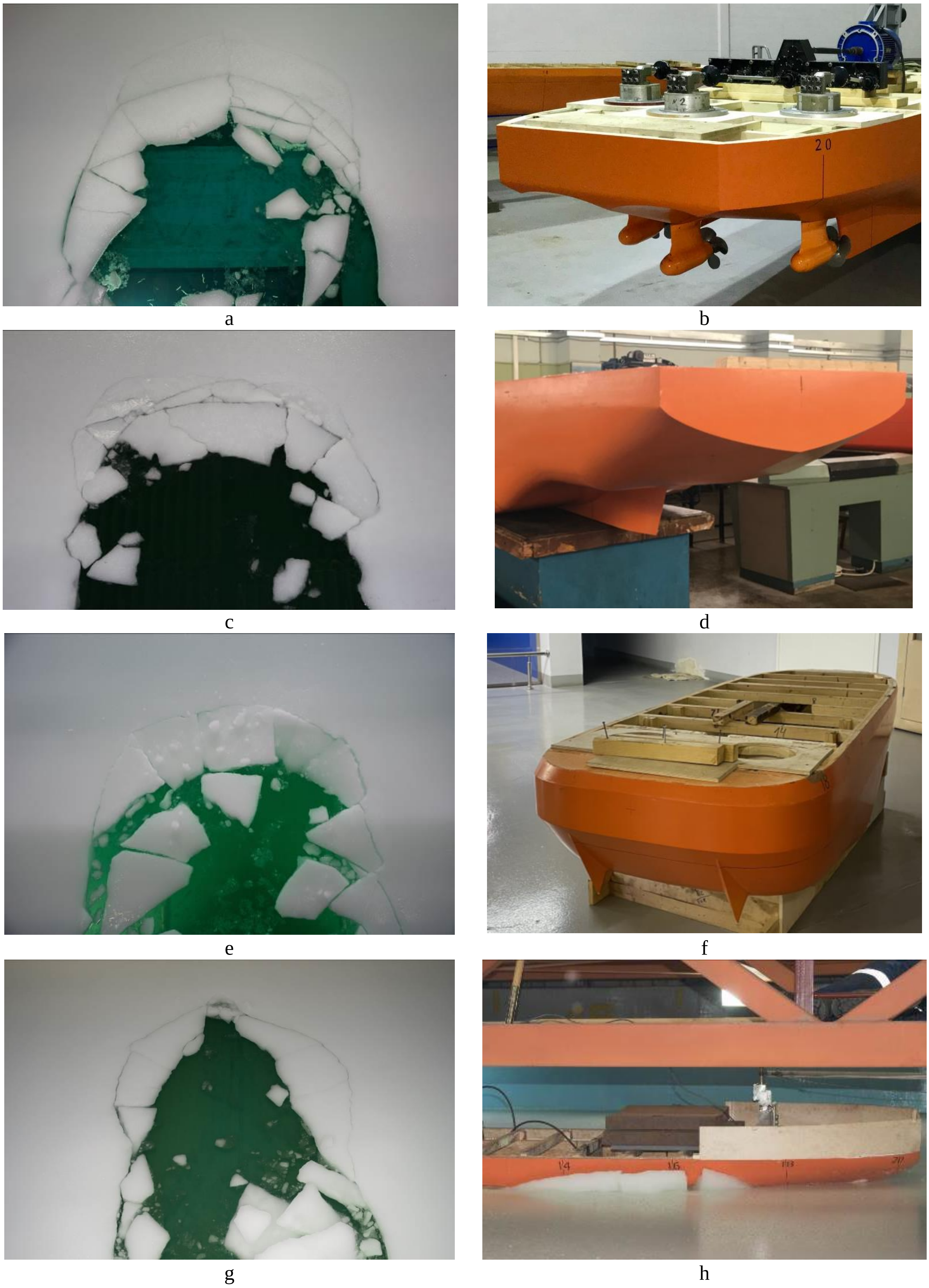

Figure 2 – Typical pieces of ice broken out by ship stern: a,b – tanker with 3 podded propellers; c,d – icebreaking vessel with 2 podded propellers; e,f – tugboat with 2 podded propellers; g,h – icebreaker with traditional propellers

– icebreaking vessel equipped with 2 podded propellers (Figure 2d). Main dimensions: length – 0.6*L*; breadth – 0.65*B*, draught – 0.8*T*;

– tugboat equipped with 2 podded propellers. Main dimensions: length – 0.15*L*; breadth – 0.27*B*, draught – 0.47*T* (Figure 2f).

It can be concluded following a detailed considerations of each stern trace that the ice breaking patterns of ship hulls have much in common (Figures 2a, 2c and 2e), while the main dimensions and hull forms are absolutely different. Predominantly, large sectors of ice are formed around the entire hull breadth, over the afterbody waterline. The observed shapes of these ice fragments are determined by the long ice contact zone of stern, which is in good agreement with the model obtained by D.E. Kheisin (Kheisin, 1960).

Additionally, a pattern of ice breaking by stern is shown for an icebreaker outfitted with traditional propellers (Figure 2g). The stern has a wedge-like shape. Observations show a certain difference of ice breaking patterns of the traditional icebreaker as compared with the above vessels equipped with podded propellers. The main feature is that ice sectors are only formed along the ship sides, while in way of the longitudinal centerplane the large ice fragments are absent at all. The ship hull is turning and submerging these ice pieces.

Let us consider in detail the mechanics of processes to work out the mechanism of ice breaking by stern.

Mechanics of ice breaking by stern

When the ship stern begins to interact with the ice edge the same crushes and crumbles under contract pressures equal to the crushing strength of ice. The ice cover and stern are exposed to the total normal force F_N defined as

$$F_N = \sigma_C S_C \tag{1}$$

where σ_C – crushing strength of ice; S_C – crushing surface area.

The vertical component of this normal force is $F_B = F_N \cos\varphi_a$ (φ_a –angle of stern overhang in longitudinal centerplane) causes the flexural ice breaking, as well as ship trim by bow. In the first approximation the trim angle ψ can be found from the formula

$$\psi = \frac{F_B L}{2gDH} \tag{2}$$

where L – ship length; g – gravitational acceleration; D – ship mass; H – longitudinal metacentric height.

The results of measurements in the ice basin show that the trim angle ψ is seldom higher than 1–2°. However, even these small values of ψ cause vertical displacements of stern points over $y = \frac{L}{2}\sin\psi \approx \frac{L}{2}\psi$. Depending on the ship length these may be comparable with the ice thickness. The following situation may arise. The vertical component of normal force exerted by the stern on ice edge is not high enough to break it. While the vertical force induces the ship trim by bow. Vertical displacements of the stern points is sufficient to move the ice edge under the stern. This situation may arise when the overhang immersion h_a satisfies the inequality

$$h_a \le \frac{L}{2}\psi = \frac{F_B L^2}{4gDH} \tag{3}$$

In calculation of relation (3), different options are possible depending on the type of stern structure.

1. If the stern has no protective ice horns before pods, then after the ice edge partly forced under the stern the load will be redistributed on the ice edge. In the vicinity of the longitudinal centerplane the load on ice edge from the stern is reduced, while the load increases in way of abrupt changes of waterline curves. The ice failure occurs according to two possible scenarios. Depending on the stern geometric dimensions and ice thickness, each area of increased load would induce local ice failures, or the load on the ice edge would be taken by the ice sheet as a global load. Then the ice breaking is accompanied with formation of a large ice fragment comparable with the stern size.

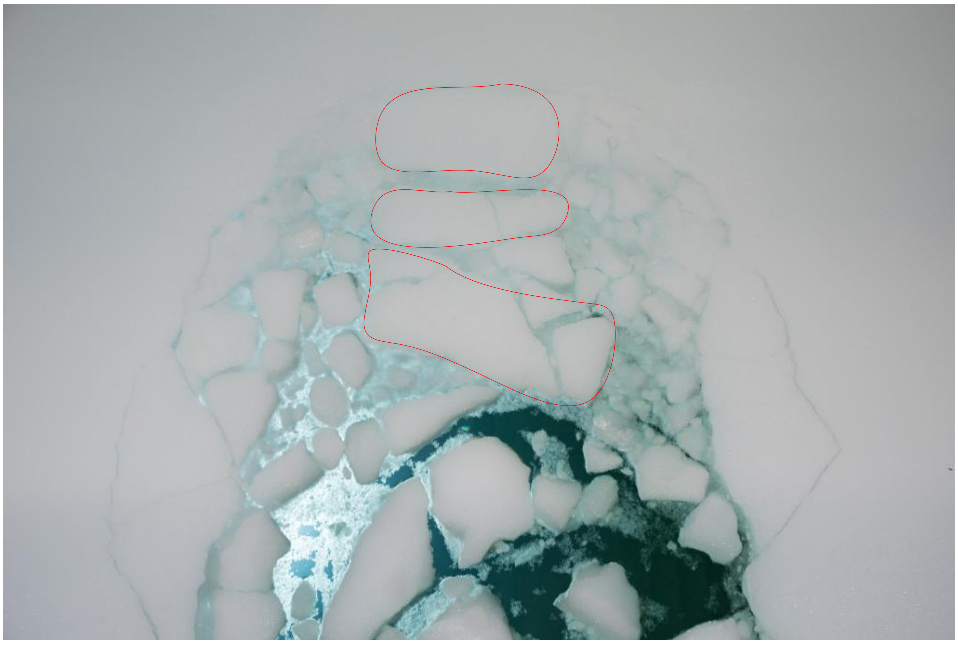

Figure 3 –Large ice fragments broken out by the stern with two pods

2. If protective ice horns are sufficiently extended, they take care of the entire ice sheet contact with ship hull. Here, also the above situation may occur when depending on the ice thickness and specific stern structure the ice horns may cause local ice failures by bending or form a rather large ice fragment. Somewhat limiting case of local ice failures on ice horns and pod struts is cutting of ice by these structural elements. It may lead to large ice pieces, which could stick in-between two pods (Figure 3).

Experimental investigations conducted at the Krylov State Research Centre in recent years have shown that the ice resistance, when the ship is moving astern in solid ice, strongly depends on the one or another scenario in question. A preliminary conclusion can be inferred from the analysis that the ship has the least resistance if inequality (3) is not satisfied. In one experiment an increase of the ship draught by about 7% caused a 18–20% reduction of the ice resistance. The main effect of a change in ship draught was a change in the ice breaking pattern by stern. There was no longer penetration of unbroken ice edge under stern. An increase in the ship draught caused, first, h_a to increase, secondly, the water displacement D to grow.

INFLUENCE OF PROPULSION SYSTEM ON SHIP MOTION ASTERN

Analysis of the propulsion system influence on the character of ship motion astern is primarily required for correct setting and performance of model tests. Unlike full-scale conditions where the main motion parameters are uniquely defined by the level of power delivered to propellers, as well as by the thickness and strength of ice, the model experiment gives more freedom in specification of motion parameters. In accordance with the practices adopted in some ice basin the ice resistance to ship motion astern is determined in the towed propulsion tests with operating model propellers (Figure 4) (Dobrodeev et al., 2015). In this case the model speed is uniquely governed by the towing carriage. Formally, the method makes it possible to specify any revolution number for the propellers if this number remains constant in ice conditions and in ice-free water.

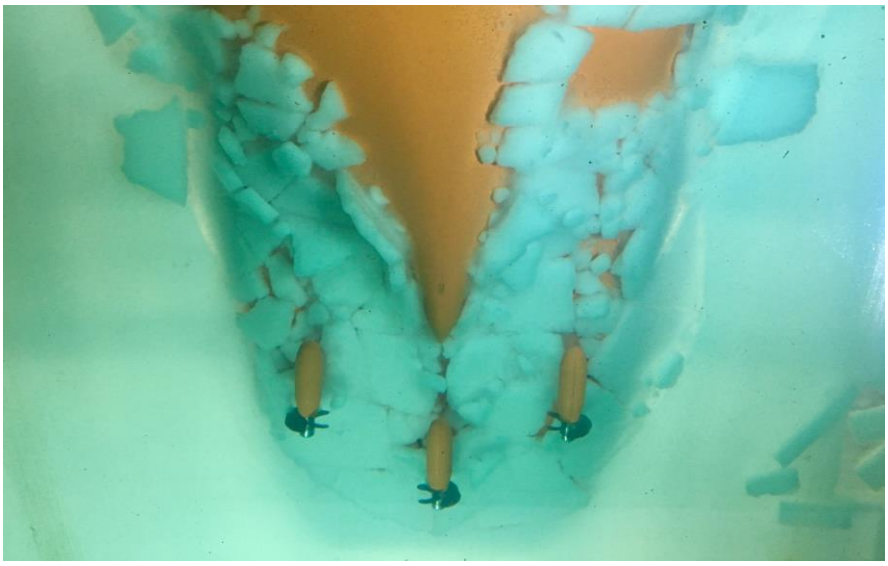

Figure 4 – Towed propulsion tests with operating propellers in ice basin

However, visual observations of ship models during ice resistance studies astern show that patterns of flow of submerged ice pieces around hull changes depending on the level of hydrodynamic load on propeller (number of revolutions and model speed). It may significantly affect the model ice resistance.

The Krylov Centre has many times investigated in the ice basin how changes in the propeller revolutions influences the ice resistance measurements. E.g., (Lopashev, 2017) gives a graph of model's relative resistance versus speed. For verification of the obtained data this graph is complemented with the data obtained for a heavy-tonnage ship sailing astern at different numbers of revolution. In particular, the graph is added with the data obtained for 63% propeller RPM corresponding to 100% ship power for one of the YamalMax LNG carrier concepts at ship speeds 2 to 5 knots in level solid ice of 1.5 m thickness (Figure 5).

This graph is developed based on the analysis of ice resistance of several ship models and provides conclusive evidences that reduction in the propeller revolutions leads to increased ice resistance of the model astern.

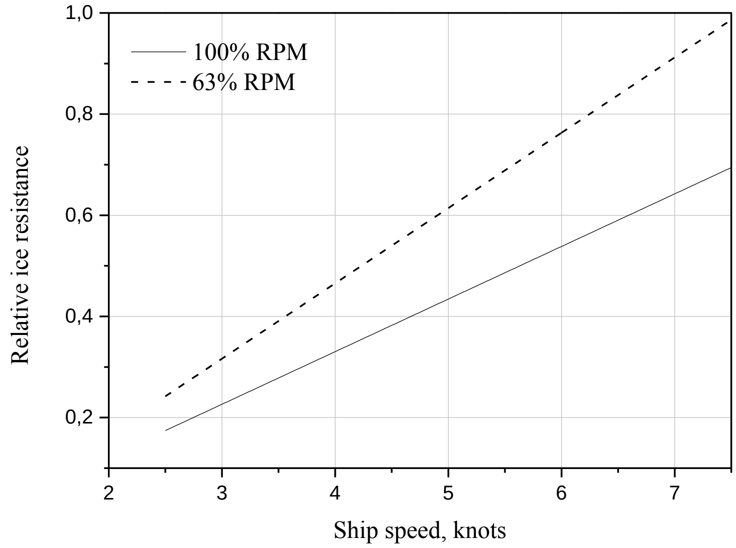

Figure 5 – Relative resistance versus model speed and propeller RPM in astern mode

The obtained data also point out that it is necessary to correctly specify the number of propeller revolutions for ice resistance experiments when the ship is moving astern.

Finding of the required number of revolutions is not a trivial task in the ship propulsion theory. The point is that it is impossible to choose the number of revolutions for a ship using the common techniques of propulsion performance evaluations. Some parameters required for calculations (wake fraction) become negative at the ship speeds and hydrodynamic loads on propellers typical of navigation in ice, and cannot not be used. For this reason the pulling performance of icebreakers and ice-going vessels have long been defined approximately, based on the bollard pull data and relatively high speeds in ice-free water. Determination of revolution numbers is not possible at all. These have been estimated from bollard pull calculations.

To overcome this difficulty the Krylov Centre researchers have devised a new alternative system of coefficients for the propeller/hull interaction, which is free from the shortcomings typical of the traditional system Kanevskii & Klubnichkin, 2017). The ship is sailing at small advance coefficients J_{oS}[1]. At these values of the advance coefficient the classical system of coefficients is not good because the wake fraction turns negative at a certain advance coefficient and tend to minus infinity at bollard pull conditions. The tests verified that the new bollard-pull system of interaction coefficient is equivalent to the traditional system. The new system was used for calculations of ice propulsion performance of icebreakers and ice-going vessels in ahead mode (Kanevskii et al, 2018), which demonstrated high efficiency of novel methods and possibility to estimate all propulsion parameters in ice.

At present studies are under way on the use of the bollard-pull system of interaction coefficients for estimations of astern mode. These coefficients make it possible to calculate the number of propeller revolutions for each mode of astern operation to enable the modeling of propeller slipstream around the underwater hull and ice clearing of the hull.

[1] Small advance coefficients are within 0 to 0.3.

CONCLUSION

Important features of ship sailing astern in ice have been considered. It concerns the type of ice breaking patterns by ship stern and the influence of correct choice of propeller revolutions on the model test results for estimation of ice resistance.

Description of the qualitative patterns of ice breaking by stern is enabled by good visualization tools showing the processes of stern and propeller interaction with ice. A detailed analysis of more than a dozen various models has identified some common features and made it possible to provide a qualitative picture of the observed phenomena. Based on this qualitative picture, one can move to work out a more detailed mathematical model of phenomena.

The second aspect of the problem considered in the paper is of equal importance. The main drawback of the existing calculation methods is the lack of due account of propeller influence on the level of ice resistance sustained by ship. For correct consideration it is required to understand the type of influence which hydrodynamic loads on propeller have on the ice resistance. The data submitted in the paper provide an opportunity to assess this influence.

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