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Method for estimating the propulsion performance of a multi-shaft icebreaker in ice field

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ABSTRACT

A method is suggested for estimating the propulsion performance of a multi-shaft icebreaker in ice field. The initial data input for the method is the specified distribution of the main engine power by propulsive units of different types. This study assumes that the propulsive units of a multi-shaft ship differ either by geometry particulars or by operating conditions given the same geometry.

Ice resistance of the multi-shaft icebreaker is found based on model tests in ice basin. In this study it is assumed that the ice resistance versus ship speed in ice is given.

Hydrodynamic performance of propulsors is determined from open-water model tests. Full-scale hydrodynamic characteristics of propulsors are obtained by the ITTC'78 method.

Hull/propeller interaction coefficients are found from self-propelled model tests in towing tank. The test results are processed using a new alternative system for estimation of hull/propeller interaction coefficients. The self-propelled model tests were performed at the specified distribution of power delivered to propulsors of different types. Based on the self-propelled model tests the total thrust-deduction coefficient is determined. For each type of propulsor the factors of hull effect on thrust and torque are determined.

The proposed method enables estimation of all propulsion characteristics for the icebreaker at speeds typical of operations in ice. The said propulsion characteristics include the speeds of revolution and effective thrust of all propulsors, and, therefore, this method can be used to analyse full-scale trial data. The paper contains case studies to illustrate application of the method for analysis of the full-scale data from recent icebreaker trials.

KEY WORDS: Icebreaker; Propulsion performance; Ice field; Multi-shaft ship.

INTRODUCTION

Ship performance in ice has two components: ice resistance and efficiency of ship propulsive system. In the vast majority of studies these two aspects of the ship performance in ice are addressed separately. Concerted efforts have considerably advanced the experimental and analytical methods for evaluation of ice resistance. ITTC has elaborated detailed recommendations and guidelines for model tests in ice basins covering experiments with non-propelled (ITTC 7.5-02-04-02.1, 2017) as well as propelled (ITTC 7.5-02-04-02.2, 2017) models. These recommendations enable highly accurate ice resistance predictions for icebreakers and ships under design. Up-to-date techniques are employed for ice resistance computations (Lindqvist, 1989; Su et al., 1989 & 2011; Tan et al., 2014; Valanto, 2009), which offer enhanced predicting capabilities. All these tools make it possible to determine the ice resistance with a sufficient accuracy for design purposes, in particular at close to limiting ship speeds in ice.

More often than not studies on operation of icebreaker propulsive systems in ice were limited to investigation of propeller/ice interactions. Significant progress has also been achieved in this field providing good strength of propulsive systems, including podded thrusters, as well as deep insights into dynamics of the propulsor-shaft-engine system in ice conditions (Andryushin et al., 2013; Appolonov et al., 2006; Dobrodeev et al., 2017; Ikonen et al., 2015; Sampson et al., 2009; Juurmaa et al., 1981). However, the hydrodynamic performance of icebreaker propulsors has not been duly addressed. Here one can mention only the studies of Alekseev et al. (1993) and Narita and Yamaguchi (1981) concerned with some specific hydrodynamic aspects of icebreaker propulsion systems. It can be asserted that presently there are no available methods for estimation of pulling thrust performance in ice for icebreakers and ice-going vessels. Effective (net) thrust of propulsion systems is found by various approximations based on bollard pull estimates. E.g., Su et al. (2010) suggest the following equation:

$$T_{net} = T_B \left[1 - \frac{1}{3}\frac{V_I}{V_{ow}} - \frac{2}{3}\left(\frac{V_I}{V_{ow}}\right)^2 \right] \text{ [kN]}, \quad (1)$$

where T_B –bollard thrust; V_I, V_{ow} – ship speed in ice and in open water at constant power.

This situation involves some technical difficulties, however the state of the art has been improved due to recent studies (Kanevskii and Klubnichkin, 2017; Kanevskii et al., 2018).

Operational challenges often require multi-shaft propulsion solutions for icebreakers. In this case the above-said estimations become more difficult to perform even for ice-free navigation (ITTC 7.5-02-03-01.7, 2017). For selecting the most effective propulsion systems it is necessary to have a method for predicting propulsion performance of a multi-shaft icebreaker in ice field. In this context, it is urgently needed to develop such method for dealing with the propulsion performance of multi-shaft icebreakers in ice field.

MULTI-SHAFT SHIP

For the purposes of this study the multi-shaft ship is understood as a vessel having at least 2 different types of propulsors. Propulsive units of a multi-shaft ship differ either by geometry particulars or by operating conditions at the same geometry. The ship can be equipped with N different types of propulsors. The number of units in each propulsor type is specified as Z_{P1}, …, Z_{Pi} ,…, Z_{PN}.

A common twin-shaft vessel with two screw propellers (port & starboard) is not considered as a multi-shaft ship here. However, a similar twin-screw ship having some special hull design features, like moonpool, asymmetrical with respect to the ship centerline, falls under the multi-shaft vessel category. The point is that a moonpool on one of the ship sides would alter the propeller/hull interaction coefficients so that operating conditions for the propulsors would be different.

It is assumed that the multi-shaft vessel can equipped with any number of different types of propulsors. For a realistic ship the number of propulsor types is usually not more than 3. It is assumed that all types of propulsors considered in this paper can be modelled in open water conditions to determine their individual hydrodynamic performance. Each type of propulsor is to include a screw propeller.

ICE RESISTANCE

Ice resistance of the multi-shaft icebreaker in ice field is determined from model test data obtained in ice basin. In this paper it is assumed that the ice resistance versus ship speed in given ice thickness is known.

Further, it should be noted that the ice resistance coefficients in model and full-scale conditions are equal

$$C_{IM} = C_{IS}, \tag{2}$$

"M" subscript in eq. (2) and further in the text refers to model scale, while "S" refers to full scale (ship).

Here the ice resistance coefficient is defined as:

$$C_I = \frac{2R_{ITOT}}{\rho_w V^2 S}, \tag{3}$$

where R_{ITOT} – total ice resistance (it consists of net ice resistance and water resistance in ice conditions); ρ_w – water density; V – icebreaker speed in ice; S – wetted surface area.

HYDRODYNAMIC CHARACTERISTICS OF PROPULSORS

Hydrodynamic characteristics of propulsors, namely, thrust K_{To} and torque K_{Qo} coefficients versus J_o advance coefficient are found from model test data obtained in open-water experiments for isolated propulsors. Here the subscript "o" refers to open-water test data. Open-water propeller model tests are used to determine $K_{ToM} = K_{ToM}(J_{oM})$ and $K_{QoM} = K_{QoM}(J_{oM})$.

Based on these data one can find similar relationships for the full-scale ship $K_{ToS} = K_{ToS}(J_{oS})$ and $K_{QoS} = K_{QoS}(J_{oS})$ with due account of the scale factor as recommended in ITTC 7.5-02-03-01.4, 2008.

Hydrodynamic performance of a podded propulsor (azimuth thruster) in open water conditions is characterized by the podded propulsor thrust coefficient K_{To_unit}, propeller thrust coefficient K_{To} and torque coefficient K_{Qo} in function of J_o. Extrapolation from model to full-size is done taking into consideration the scale effect. In this case the full-scale thrust coefficient of podded propulsor is determined by the analytically derived relation from Chicherin et al., 2004:

$$K_{To\_\mathrm{unitS}} = K_{To\_\mathrm{unitM}} + 0.2\left(K_{ToM} - K_{To\_\mathrm{unitM}}\right) \quad (4)$$

This method of propulsion performance estimation for multi-shaft icebreakers can be implemented using any other technique to predict full-scale hydrodynamic characteristics of propulsors, which should be found sufficiently reliable for that purpose by researchers performing the estimates.

HULL/PROPELLER INTERACTION COEFFICIENTS

For correct evaluation of hull/propeller interaction coefficients for the multi-shaft ship during self-propelled model tests it is required to ensure that the specific power at propellers is similar to that given for full-scale propellers. If this condition is met, the hull/propeller interaction coefficients are determined correctly and unambiguously.

It is found that the interaction coefficients can be obtained by self-propelled model tests under overload at one speed of the first propulsor type with a wide variation of the model speed.

The ship is sailing in ice at low advance coefficient $J_{o\,S}$. The classical system of interaction coefficients is not applicable at these values of advance coefficient because, starting from a certain value of this parameter, the wake fraction goes negative and tends to $-\infty$ at the bollard pull condition. In an effort to overcome this problem an alternative system of interaction coefficients was suggested in Kanevskii and Klubnichkin, 2017, and Kanevskii et al., 2018. The alternative system includes the thrust deduction coefficient t, which is obtained traditionally, as well as the following coefficients $i_{TB} = K_T / K_{To}$ and $i_{QB} = K_Q / K_{Qo}$. These coefficients are found using traditional model test data provided by self-propelled model experiments in the form of effective thrust loading coefficient $K_{DE} = VD_{eff} : \sqrt{\dfrac{T_E}{\rho_w Z_P}}$ extended to a general multi-shaft ship case. In this formula any effective propeller diameter D_{eff} can be assumed, e.g., equal to the diameter of the first type of propulsors or arithmetic average of all propellers in a multi-shaft ship. The main requirement is to apply the same rule to define D_{eff} in self-propelled model tests and full-scale predictions of a multi-shaft vessel.

It appears that coefficients i_{TBi} , i_{QBi} are subject to the scale effect, however this matter is yet to be studied. Nevertheless, there are some reasons to believe that the scale effect has minimum implications for icebreakers sailing in ice.

Self-propelled model tests in some hydrodynamic centers are conducted with application of some correction tow force F_D at constant model speed V_M and propeller load variation (load variation test - LVT). These tests can be logically extended to cover the multi-shaft case by modeling the same as in full-scale power distribution over propeller shafts. In the load variation tests it is assumed that $F_D = 0$ because ice resistance coefficients of model and full-scale ship are equal (2).

In LVT it is required to determine the rotational speed of the first type of propulsors when the effective thrust T_{EM} is equal to the ice resistance R_{IM}. Then at a given ship model speed V_M it yields the total thrust deduction coefficient t and the coefficients of hull effect on thrust i_{TBi} and torque i_{QBi}. LVT performed in a range of model speeds enable us to derive the following relations for hull/propeller interaction $t = t(V_M)$, $i_{TBi}=i_{TBi}(V_M)$, $i_{QBi}=i_{QBi}(V_M)$, $i = 1,\dots, N$, that are similar to the relations for K_{DE} given above.

METHOD FOR PROPULSION PERFORMANCE ESTIMATES

Initial data inputs for these calculations are the ice resistance R_{ITOTS} versus V_S, number of propulsors *N*, hydrodynamic and geometric characteristics of open-water propulsors of full-scale ship, power delivered to propulsors, and relations for hull/propeller interaction coefficients. These data are used to calculate the thrust load coefficient K_{DQiS} for each type of propulsor from (Fig.1):

$$K_{DQi\,S} = \sqrt{\frac{J_{oiS}^3}{2\pi K_{QoiS}}} = V_{o_i\,S} \cdot D_{i\,S} \cdot \sqrt{\frac{\rho_s V_{oi\,S}}{P_{oi}}} \quad (5)$$

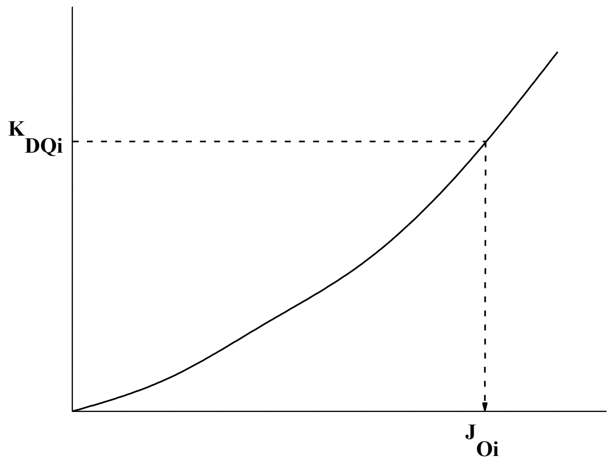


Fig. 1 – Thrust load coefficient K_{DQiS} versus advance coefficient of propeller J_{oS}

The purpose of estimates is to find the effective thrust of ship's propulsion system, as well as other propulsion characteristics of the icebreaker.
In the process of these calculations a number of ship speeds V_{Sj} are assumed. Then the effective thrust loading coefficient K_{DE} is calculated, assuming that the effective thrust of propulsion system is equal to the total ice resistance, and the hull/propeller interaction coefficients as well as the hull efficiency η_{Hi} are found:

$$\eta_{Hi} = (1-t)\frac{i_{TBi}}{i_{QBi}} \quad (6).$$

Then one can find the power consumed by open-water propellers P_{oi}:

$$P_{oi} = \frac{P_{Di}}{i_{QBi}} \text{ [kW]}, \quad (7)$$

P_{Di} - power delivered at propeller.
Considering that the flow velocity through propeller disks in open water is equal to the ship speed, one can use equation (5) to determine the torque loading coefficient and employ the same to find the advance coefficient $J_{oi\ S}$. Knowing the advance coefficient one can determine hydrodynamic coefficients of propulsors, their speed of revolution, efficiency and propulsive coefficient.
Hydrodynamic coefficients and revolution rates of propulsors are used to calculate the thrust of each propulsor in open water, and then their thrust behind hull is determined using the i_{TBi} coefficient. Knowing the thrust deduction coefficient, one can find the effective thrust of various propulsors, the torque produced by different propellers behind hull, as well as the total effective thrust of all propulsors

$$T_E = \sum_{i=1}^{N} (T_{E_i} \cdot Z_{pi}) \text{ [kN]} \quad (8)$$

Based on the found effective thrust of propulsion system in function of the ship speed, it is easy to determine the icebreaker ship in ice of given thickness. In addition, the results of these calculations can be used to find all parameters characterizing the ship propulsion performance in ice.

CASE STUDIES

Application of the proposed method is illustrated by calculations performed for diesel electric icebreakers *Vladivostok* and *Novorosiisk*. The icebreakers were built in 2015 - 2016 at Vyborg Shipyard. These are double-deckers propelled with two 360° azimuthing thruster units of 9 MW designed to the Icebreaker 6 class of the Russian Maritime Register of Shipping. Sea trials of the icebreakers were performed (Kostylev and Sazonov, 2016; Lopashev et al., 2017; Kanevskii and Klubnichkin, 2017).

Fig. 2 shows the hull/propeller coefficients estimated from the self-propelled model test data obtained in a hydrodynamic basin for all operation modes typical of icebreaker in ice.

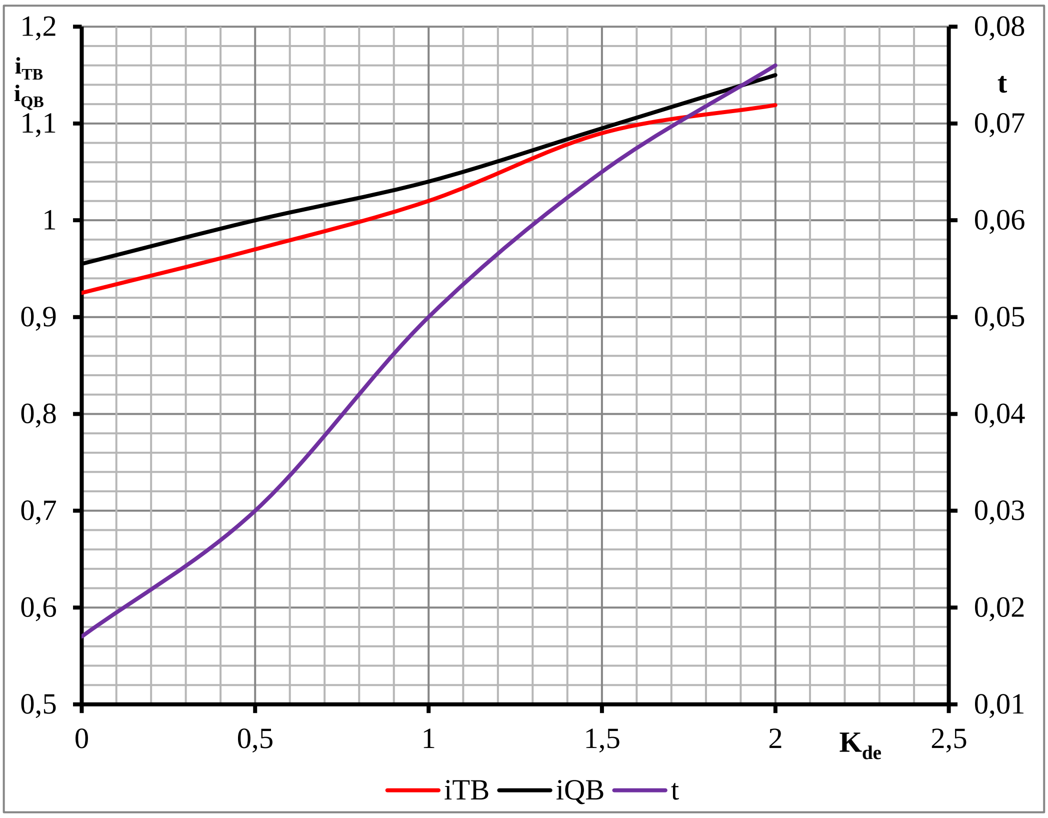
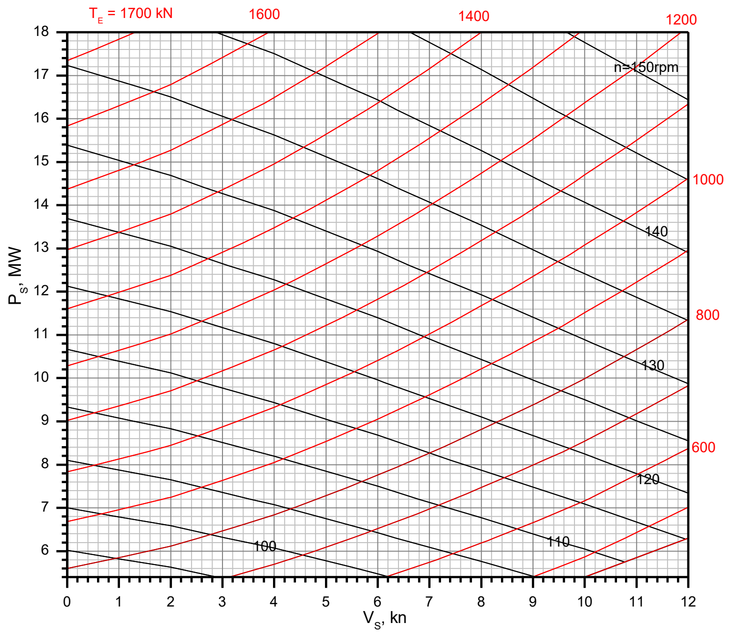


Fig.2 Hull/propeller interaction coefficients for icebreaker operation in ice

The calculation results obtained by the proposed method are summarized for convenient practical use in one diagram, see Fig. 3. This diagram relates effective thrust characteristics of icebreaker propulsion systems to the consumed power and ship speed. The diagram also contains the revolution rates of propulsors. It should be taken into account that this diagram has been plotted, assuming that the hull/propeller interaction coefficients in ice and ice-free conditions are the same.



Effective Thrust Diagram for Icebreaker 21900M

Fig. 3 Propulsion performance diagram for *Vladivostok* and *Novorosiisk* icebreakers

Fig.4 compares calculations of the effective thrust performance for icebreaker by the proposed method and empirical formula (1).

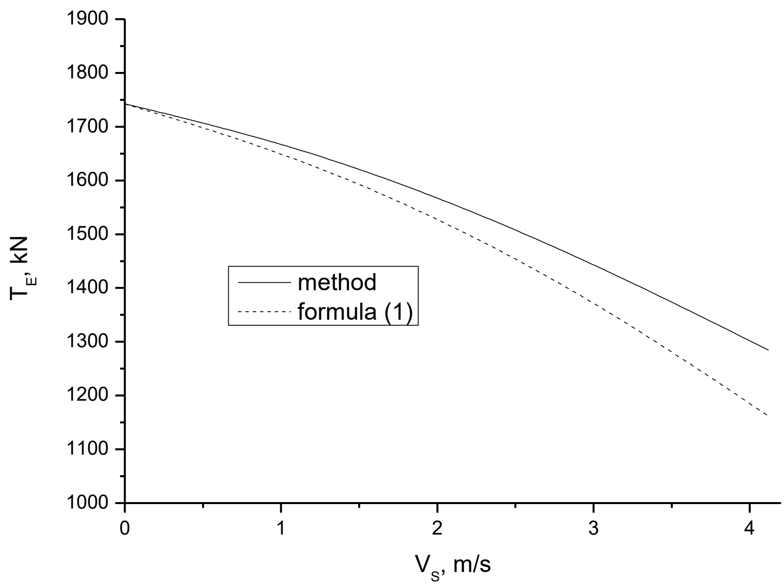


Fig. 4 Comparison of effective thrust calculations for icebreaker propulsion system by the proposed method and formula (1)

ANALYSIS OF FULL-SCALE TRIAL DATA

It is seen that the diagram of Fig.3 makes it possible to determine the pulling thrust of propulsors from full-scale measurements of power consumed by propulsors and icebreaker speed. Revolution rates of propulsors taken from the same diagram serve as indicators to prove correctness of this procedure.

For the analysis of full-scale trial data by this diagram it is required to select those parts of recorded time histories of ship speed, power and rate of propeller revolution where propellers do not show strong interaction with ice. For these sections one can estimate the effective thrust of propulsion system and, therefore, find the total ice resistance R_{ITOT}. Actually, the proposed method makes it possible to estimate the full-scale ice resistance. This possibility is an important result, enabling us to address a range of tasks. Firstly, with the ice resistance information in hand, it is possible to use the data obtained at partial power of ship's powerplant to full extent. Secondly, the ice resistance data can be used in extrapolation of full-scale trial data to other ice strength and thickness conditions, applying correction techniques that are well developed for model experiments as per ITTC 7.5-02-04-02.1, 2017.

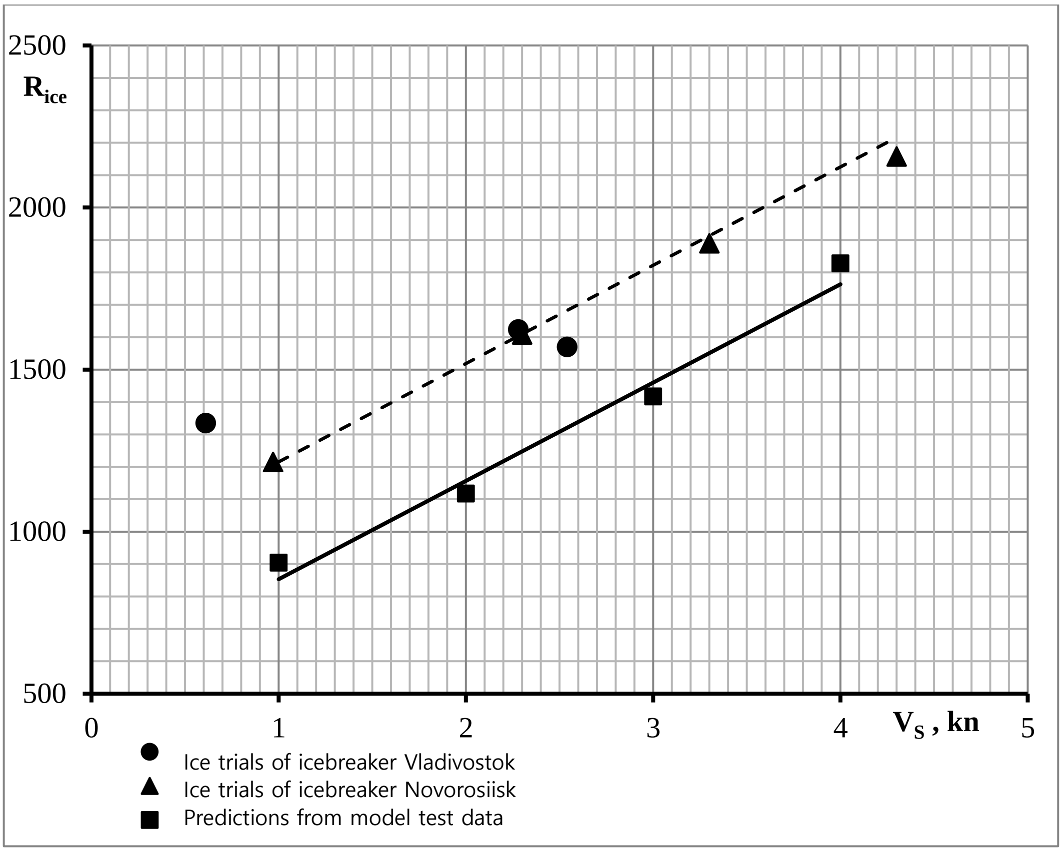


Fig. 5 Comparison of ice resistance obtained from full-scale trials and model tests

Fig.5 compares the ice resistance data obtained from full-scale trials and model tests in ice basin. The full-scale test data shown in this figure have been extrapolated and referred to the same ice strength and thickness conditions. It is seen from the analysis of this figure that both full-scale trials and model tests indicate the same trend in ice resistance variation with ship speed increase. Also, rather large discrepancies are observed between the ice resistance values measured in full-scale and predicted from model tests. A number of reasons can be mentioned why there is no good agreement between model predictions and full-scale data. The major of these are as follows:

1. Possible scale effect on the new system of interaction coefficients, as well as the influence of an ice jacket, which covers the underwater hull of icebreaker, on the values of these coefficients.

2. Possible scale effect on ice resistance, as well as errors in model correction methods applied to full-scale trial data.

3. Incorrect account of snow cover in the analysis of ice test data causing deviations from the

reference ice thickness.

4. Neglecting of errors in ice thickness, ice strength and snow cover thickness determined during full-scale trials.

CONCLUSIONS

Actually, the possible causes of result discrepancies mentioned above are setting new tasks for researchers that can be addressed with the method proposed here for estimation of ship propulsion performance in ice. The method suggested in this paper can be used as a tool for in-depth investigation of complex processes associated with navigation in ice.

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