Method for estimation of icebreaker propulsion performance in ice

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Abstract. Classical methods of ship propulsion estimations based on the traditionally applied system of hull and propeller interaction coefficients are not suitable for prediction of icebreaker performance in ice. This is because the wake fraction tends to assume negative values in operating conditions typical of navigation in ice. This paper suggests an alternative system of hull/propeller interaction coefficients to overcome the problem. The alternative system comprises the thrust deduction factor \( t \) and the factors allowing for hull effect on thrust \( i_{TB} \) and hull effect on torque \( i_{QB} \). An alternative method of ship propulsion performance estimations is developed based on this system of coefficients to take into account all characteristics of icebreaker sailing in ice. The method was used to analyze the full-scale data obtained from sea trials of the icebreakers Vladivostok and Novorosiisk. The initial data inputs for the analysis were ship speed in ice and consumed power measured during the sea trials. The number of propeller revolutions and ice resistance were calculated. The estimated propeller revolutions were compared with the full-scale data gathered during the sea trials in ice. The ice resistance was compared with the predictions based on model tests in ice basin. It is shown that at slow speeds in ice, ranging from 0.5 to 5.0 knots, the predicted number of propeller revolutions is in good agreement with the data measured during the sea trials. Propulsion performance of the Vladivostok icebreaker in 1.5-m thick ice was estimated.

1. Introduction

In view of the modern developments in Arctic shipping it is required to increase the operational efficiency of icebreakers and ice-going vessels and, in this connection, to drastically raise the accuracy of predictions regarding the propulsion performance of ships in ice. The propulsion performance in ice has two components: ice resistance and thrust of propulsion system. Recently the most vivid progress has been achieved in development of experimental [1, 2] and computational [3–7] methods for ice resistance evaluations. All these references as well as many other studies provide for ice resistance predictions with acceptable accuracy for design purposes, in particular for the cases of close-to-limit ice conditions.

A vast majority of studies on icebreaker propulsion systems have focused only on the interaction between ice and propellers or propulsion pods with an emphasis on strength considerations [8–12]. However, little attention has been paid to the hydrodynamic aspects of icebreaker propulsions. Only one reference can be cited [13] where some specific hydrodynamic issues of icebreaker propulsors have been addressed, e.g. cavitation phenomena.

Traditional approaches used today enable us to confidently predict only the limit ice-going capability of icebreakers and vessels, i.e. the maximum thickness of ice field where the ship is able to...
sail without stopping at a given power of main engines. However, it is impossible to predict the thrust, torque, speed of revolutions and efficiency of icebreaker propulsors in a broader range of ice navigation conditions, which is necessary for optimizing operation of icebreakers and ice-class vessels. In this context it appears that prediction of ship propulsion in ice for the entire spectrum of operating conditions is very much relevant today.

2. Traditional and “bollard pull” system of hull/propeller interaction coefficients

The traditional system of hull/propeller interaction coefficients is made up of three factors: $t$ – thrust deduction coefficient, $w$ – wake fraction and $i_Q$ – factor allowing for non-uniform wake effect on torque. The values of these coefficients and their dependence on propeller load are determined experimentally by self-propelled model tests, comparing propeller curves obtained in open water and behind model hull. This comparison is done at equal thrust coefficients in open water $K_{T0}$ and behind model hull $K_T$. Figure 1 gives a typical curve of wake fraction versus effective thrust of propulsors $K_{DE}$, showing that the wake fraction turns negative at $K_{DE}$ variations in the range from 0 to 1.0, which is typical for ice sailing. The traditional approach to propulsion performance prediction in this case is no longer applicable because of negative wave fraction values.

![Figure 1. Typical results obtained using traditional hull/propeller interaction coefficients](image_url)

The alternative system of interaction coefficients is based on the data traditionally obtained from towing tank experiments [14]. Coefficients are determined at a given constant advance ratio of propeller $J$. For this purpose the test data plots are used to pick up the values of thrust and torque in open water $K_{T0}, K_{Q0}$ and behind model hull $K_T, K_Q$, as well as effective thrust coefficient $K_E$. The interaction coefficients are defined by the following equations:
factor allowing for hull effect on thrust $i_T = \frac{K_T(J)}{K_{T0}(J)}$

- factor allowing for hull effect on torque $i_Q = \frac{K_Q(J)}{K_{Q0}(J)}$

- thrust deduction factor $t = 1 - \frac{K_E(J)}{K_T(J)}$

The thrust deduction factor is estimated in the same way as it is done under the traditional approach.

A specific feature of the “bollard pull” approach is that flow velocities in open water and behind model hull are equal, hence the advance ratios are also equal, however, the propeller thrusts in this case are different. The propulsive efficiency $\eta$ in the “bollard pull” approach is defined as:

$$\eta = \eta_s i_T \frac{1-t}{i_Q}$$

where $\eta_s$ - shafting efficiency, $\eta_0$ - propeller efficiency in open water.

Figure 2 shows values of alternative interaction coefficients for a four-shaft icebreaker sailing ahead.

**Figure 2.** Alternative interaction coefficients versus load coefficient $K_{de}$ for icebreaker.

### 3. Propulsion performance estimations for icebreaker

Introduction of the “bollard pull” coefficients system enabled us to work out a method for estimation of icebreaker propulsion performance in ice environment. The main assumption is that the hull/propeller interaction coefficients estimated based the “bollard pull” approach can be extended to the icebreaker operation mode in ice. It is a quite conventional assumption that was used before to study ship sailing in ice. The efforts to develop a new method required certain correction of the traditional performance prediction technique as well as generalization of results to the case of a multi-
shaft vessel whose propulsion system comprises different type propulsive units, e.g. conventional screw propellers and podded thrusters.

The new approach makes it possible to estimate the revolutions and thrust of propulsors. Figure 3 shows a diagram relating all main characteristics of icebreaker performance in ice: speed, thrust and number of revolutions.

![Figure 3. Propulsion performance diagram for icebreaker Pr.21900m](image)

4. Application of results
The new method is applicable to a range of practical tasks in the design of icebreakers. The main advantages are new opportunities in the analysis of full-scale data from icebreaker sea trials, insights into the ice influence on hydrodynamic characteristics of icebreakers, more accurate test in ice basins with self-propelled models of icebreakers.

Sea trials. As it is seen from the diagram of Figure 3 it is possible to find the pulling thrust developed by propulsors based on the power and speed of the icebreaker measured in sea trials. The number of propulsor revolutions also determined from the above diagram serves as an indicator to confirm the procedure correctness.

If we pick the records of ship speed, power and propeller revolutions at the sections where propellers do not show any significant interaction with ice, it is possible to estimate the thrust of propulsion system and, therefore, ice resistance for these sections. Actually, the suggested method makes it possible to estimate the ice resistance in full scale conditions. With this capability of estimating full-scale ice resistance one can address a range of issues. In the analysis of full-scale data the information about ship ice resistance enables us, first, to make full use of the measurements taken at partial power outputs of ship power plant. Secondly, the ice resistance data enable extrapolation of full-scale test results to different ice strength and thickness values using well-known correction techniques employed in model experiments. Figure 4 illustrates results of full-scale data processing. It shows the speed of Vladivostok icebreaker versus ice thickness referred to a standard ice bending strength of 500 kPa, as per full-scale trial data [15]. Squares on the graph refer to the results obtained.
by traditional processing method with extrapolation of power and speed data. Circles refer to the results of ice resistance extrapolations by formulas used in model experiments. The results are in good agreement.

Figure 4. Speed vs ice thickness obtained by different methods for the Vladivostok icebreaker

Investigation of interaction coefficients in ice conditions. Investigation of hull/propeller interaction coefficients for a ship sailing in ice is a very challenging task that has not been resolved yet. One of the reasons is negative wake fractions mentioned above. However, our alternative system of interaction coefficients brings us closer to the solution of this problem. The new system enables us to examine ice effects on the interaction coefficients both in model experiments and in the analysis of full-scale trials.

The values of interaction coefficients under the alternative method can be obtained by testing self-propelled ship models towed in ice basin by towing carriage at constant speed in ice field. During these tests the frequency of propeller revolutions is varied to change $K_{DE}$. Model experiments in ice field with variation of model speed at constant frequency of propeller revolutions cannot be used for evaluation of hull/propeller interaction coefficients because in this case ice pieces adjacent to the underwater hull change their size [16]. Obviously, it may have significant influence on the coefficient values. The functions $K_T = f(J)$ and $K_Q = f(J)$ obtained from ice tests can be used to determine the alternative system coefficients. Then their comparison with the coefficients obtained in open water enables us to judge the ice effect.

Sea trial data can also provide information about hull/propeller interaction coefficients in ice. If propeller revolutions measured in full scale are different from predictions, e.g. based on the diagram of Figure 3, then it is always possible to choose an appropriate correction factor to adjust the assumed coefficient values and remove discrepancies in the frequency of propeller revolutions. With accumulation of statistical data from full-scale trials of various ships it would be possible to generalize the results and derive empirical relationships for interaction coefficients in ice.

Calculation of propulsion performance in ice for model conditions (with stock propellers) make it possible to set the frequency of propeller revolutions more accurately in model tests to better simulate real conditions. This selection of propeller revolutions is most important when slipstreams of
propellers may have effect on the ice on the underwater hull of model (sailing astern, bow propellers, etc.)

5. Conclusions
The alternative system of hull/propeller interaction coefficients is helpful in addressing a broad range of issues related to ship propulsion performance in ice. In addition to estimation of critical icebreaker parameters in ice: power, propeller revolutions and pulling thrust, the proposed system of coefficients paves the way for systematic studies on hull/propeller interaction coefficients in ice, providing requisite “initial conditions” for this purpose.

The alternative system of interaction coefficients enables rather accurate predictions of ice resistance for full-scale sea trials, increasing the efficiency of such trials. Also, the ice resistance calculations may well be used by designers of ship engines for their improvement.

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