POAC'25
St. John's, Newfoundland and Labrador, Canada

Proceedings of the 28th International Conference on Port and Ocean Engineering under Arctic Conditions
Jul 13-17, 2025
St. John's, Newfoundland and Labrador
Canada

Resistance components of a double-acting ship under stern-first icebreaking: Experimental methodology and preliminary results

Jianqiao Sun[1, 3], Yan Huang[1, 2, 3], Jinyuan Wang[1]

[1] School of Civil Engineering, Tianjin University, Tianjin, China
[2] State Key Laboratory of Hydraulic Engineering Intelligent Construction and Operation, Tianjin University, Tianjin, China
[3] Tianjin Key Laboratory of Port and Ocean Engineering, Tianjin University, Tianjin, China

ABSTRACT

For double-acting ships under stern-first icebreaking mode, the empirical or semi-empirical formulas for a straightforward assessment of the ice resistance are still lacking. To investigate the mechanism and composition of the stern-first ice resistance for a double-acting ship with twin-pod propulsion, a series of model tests in ice tank has been conducted. The methodology for the model tests is to achieve separate and simultaneous measurement of the icebreaking resistance component by the stern and the appendage resistance by the pods. Another important factor considered in the model test is the influence of propeller rate on the icebreaking, submersion, and pod resistance components.

In this paper, the model test configuration and procedures for the analysis of the stern-first ice resistance components are provided. A partial stern model is used for the assessment of the icebreaking resistance, accompanied by two separately mounted pod models for the measurement of the appendage resistance. The relative position of these models is kept consistent with the full-scale ship, and the total resistance in ice is obtained from another test run with an entire ship model. Both test series are conducted under several propeller rates including zero. Preliminary results indicate that the icebreaking and pod resistance components decrease with propeller rate, while the submersion resistance presents an opposite trend.

KEY WORDS: Double-acting ship; Stern-first mode; Ice resistance; Ice tank test.

INTRODUCTION

The azimuthing podded propulsion system provides an excellent solution for the maneuverability of ships in ice and also promotes the development of the Double Acting Ship (DAS) concept for ice operation (Juurmaa et al., 2001). Compared to conventional icebreakers, The DAS can balance open water performance and icebreaking capability: the bow design can address open water and thin ice conditions, with some ships retaining the bulbous bow to reduce the wave-making resistance during open water navigation; the stern adopts a downward icebreaking configuration similar to the conventional icebreaking bow, allowing the ship to operate in heavy ice conditions under stern-first mode (Wilkman and Mattsson, 2007). Consequently, the ice resistance under stern-first mode can be a critical factor governing the basic design of the DAS. As the boom in Arctic shipping, tourism and resource exploitation in the past decades, polar ships are required to have higher ice classes, implying that the DAS operating in the stern-first mode will encounter thicker and stronger ice features. Therefore, reliable predictions of ice resistance under stern-first mode are needed to support the optimization of stern hull lines and selection of main engine power during the basic design stage.

For the DAS, the stern is typically equipped with an azimuthing podded propulsion system, which is located very close to the area where the stern breaks and pushes the ice downwards, thereby altering the ship-ice interaction processes compared to those under bow-first mode. As a prominent external structure attached to the stern integrating traditional propellers, shafts, and rudders, the pod unit has been explicitly recognized in many ice class rules for its importance as an appendage subject to ice loads (Appolonov et al., 2011; DNV, 2021). This implies that the evaluation of the appendage resistance by the pod unit should be an integral part of the experimental prediction of ship resistance in ice. Furthermore, the frequent propeller-ice interaction and the flushing effect by the propeller wake in stern-first scenarios will significantly alter the flow field around the ship hull and may further affect the spatial distribution of broken ice floes under the bottom. Each of the above factors can cause variations in ice resistance when running astern, and the resistance components are far more complicated than those of running ahead.

Currently, the recommended procedures and guidelines by the International Towing Tank Conference (ITTC) apply mostly to the bow-first icebreaking scenarios (ITTC, 2017). For stern-first mode, specific experimental methods for the prediction of ice resistance and the analysis of its components are still needed to be developed. To address this issue, this paper aims to explore an approach on simulating the stern-first icebreaking process in ice tank, by which analyses on the resistance components and their variations with the governing factors can be achieved. Based on a thorough discussion on the stern-first icebreaking process and the existing methods for the measurements of ice resistance components, principles for the breakdown and separate measurements of the ice resistance components under stern-first mode are proposed. Preliminary model test results on a twin-pod propulsion ship (Icebreaker *Xue Long 2*) are also provided.

STERN-FIRST ICE RESISTANCE

The breaking of ice in front of a ship is a multi-factor involved physical process, primarily controlled by hull geometry, ice condition and the relative motion between ship and ice. For sea ice, the flexural strength is generally lower than its compressive strength. Thus, the ice load resulting from the bending failure of ice will be lower than that generated by the crushing failure under similar ice conditions. Consequently, compared to ships navigating in open water, achieving efficient bending failure of ice ahead of the hull is a primary goal in the design of icebreaking hull forms. For conventional bow-first icebreaking ships, such design concept can be reflected in small buttock angles (e.g., stem angle) and small flare angles (measured from the horizontal), as shown in Figure 1.

Figure 1. Bow hull form of Russian icebreaker *Arktika* (Arctic.ru © Nikita Greydin).

Since the DAS's are capable of breaking the ice in both ahead and astern directions, the stern hull form is designed following largely the same principles as the bow. In addition, considering the safety of the propulsion system, efforts are made to minimize direct contact between the pod units and the intact ice. These features can be demonstrated in the buttock line design at the stern area of the DAS's currently in service, see Figure 2. However, it is worth noting that the icebreaking process under the stern-first mode differs significantly from running ahead, particularly due to the involvement of the rotating propellers in the icebreaking and clearing processes.

Figure 2. The stern of Finnish icebreaker *Polaris* (Aker Arctic, 2016)

Firstly, water beneath the sea ice can act as an elastic foundation for the downward bending deformation of ice. Under the stern-first mode, however, the rotating propellers at high speeds create a suction effect, which may change the conditions of the elastic support from the water to the ice and result in possible variations in the bending failure of the ice sheet.

Moreover, the wake field behind the propeller will further affect the drift trajectory of the broken ice pieces, causing possible alterations in the ice coverage at the ship bottom.

Each of the above effects has a direct impact on the ice resistance of the ship when running astern. Under the conventional bow-first mode, the ice resistance can be roughly divided into breaking and submersion (e.g., Lindqvist, 1989), which can be expressed by:

$$R = R_{br} + R_{sub} \quad \textbf{[1]}$$

where R represents total ice resistance, R_{br} stands for ice breaking resistance, and R_{sub} denotes submersion resistance by broken ice. Based on the empirical estimation of ice resistance under the bow-first mode, the main governing parameters of these two ice resistance components are listed in Table 1.

Table 1. Main parameters affecting the ice resistance components.

Ice resistance component	Ice parameter	Hull parameter
Breaking (R_{br})	Ice thickness (h) Flexural strength of ice (σ_f) Compressive strength of ice (σ_c) Elastic modulus (E)	Ship breadth (B) Buttock angle (γ) Waterline angle (α) Flare angle (β') Ship speed (V)
Submersion (R_{sub})	Ice thickness (h) Ice density (ρ_i) Ice-hull friction coefficient (μ)	Ship length (L) Ship draft (T) Ship breadth (B) Buttock angle (γ) Waterline angle (α) Flare angle (β') Ship speed (V)

When a ship runs ahead, the propeller is far behind the ice breaking and clearing area at the bow, and thus the rotation of the propeller may have negligible effect on the ice resistance. For the stern-first mode, the pod unit including the propeller is exposed to the broken ice pieces directly, and the appendage resistance cannot be ignored. Meanwhile, as mentioned above, the rotating propeller can influence the bending and submerging of ice at the stern area. Consequently, for the ice resistance of the ship running astern, the propeller speed will also be an important parameter, and then the ice resistance components can be further expanded to:

$$R = R_{br}(n) + R_{sub}(n) + R_{pod}(n) \quad \textbf{[2]}$$

where R_{pod} represents the appendage resistance of the pod, and n denotes propeller speed. All the resistance components are functions of n. To further quantify the individual impact of propeller rotation speed on each resistance component, taking the resistance when the propeller is not rotating (i.e., at zero speed, n=0) as the baseline, Equation 2 can be further rewritten as:

$$R = \eta_1(n)R_{br}(0) + \eta_2(n)R_{sub}(0) + \eta_3(n)R_{pod}(0) \quad \textbf{[3]}$$

where $R_{br}(0)$, $R_{sub}(0)$ and $R_{pod}(0)$ denote the stern ice breaking resistance, submersion resistance and pod appendage resistance, respectively, when the propeller is not rotating; η_1, η_2 and η_3 represent the coefficients indicating the influence of propeller rotation speed n on the resistance components R_{br}, R_{sub} and R_{pod}, respectively. In other words, η_1, η_2 and η_3 are functions of n.

EXPERIMENTAL METHODOLOGY

Existing methods and drawbacks

The prior understanding of the stern-first ice resistance will further guide the design of model tests. Currently, there are two main experimental methods for the breakdown of the ice resistance components for bow-first scenario:

—Independently measuring the submersion resistance of pre-sawn ice, and then calculating the icebreaking resistance by another test in intact level ice according to Equation 1. Such method is referred to as the "pre-sawn ice" method (Enkvist, 1983; ITTC, 2017). It involves manually pre-cutting ice into required shapes and sizes according to the approximate breaking pattern of the tested model, as shown in Figure 3. Since the ice has been pre-cut under this condition, the measured value can be attributed individually to the submersion resistance of the broken ice.

Figure 3. Cutting pattern of pre-sawn ice (ITTC, 2017)

—Independently measuring the icebreaking resistance and then calculating the submersion resistance based on the total resistance obtained in a same test according to Equation 1. The icebreaking resistance is mainly produced by the local ice pressure acting on the ship's surface when the ice is crushed or bent. This can be measured simultaneously with the total resistance by arranging specific measuring devices, such as flexible tactile sensor sheets (Huang et al., 2018; Sun and Huang, 2023).

However, both of the above methods have certain drawbacks when applied to stern-first icebreaking tests. In the first method, the cutting pattern of ice must have a strong resemblance to the broken ice produced by the ship, which is practically impossible for the stern-first scenario especially when propeller-ice interaction is involved. In the second method, the tactile sensors should be attached tightly to the model surface, which can be easily achieved for the simply curved surface of an icebreaking bow, whether it is wedge-, spoon-, or landing-craft-shaped. However for the stern of a DAS, the hull line design differs significantly from the bow or conventional stern for open water operation, which includes:

—W-shaped transverse cross-section outline, particularly for a twin-pod configuration. For stern-first icebreaking, despite the propeller suction and flushing effect, submersion of the broken ice floes is mainly guided by the stern hull form. In fact, there is some inconsistency between ice clearing and the control of the propeller inflow. To ensure the efficiency of the propellers, the stern hull lines should be designed to lead the flow longitudinally through the propeller plane. However, efficient ice clearing requires the broken ice floes be displaced sideways or laterally by the hull. To reconcile this contradiction, stern hull form with W-shaped cross-sections have been applied in many DAS's with twin-pod configuration, e.g., *Polaris*, *SCF Sakhalin*, *Mackinaw* and *Xue Long 2*. As can be seen from Figure 4, such W-shaped cross-section is not smooth and includes a concave in the middle, which brings difficulties to the attachment of the tactile sensor sheet.

Figure 4. Stern of the Chinese polar research vessel *Xue Long 2*. Dashed lines illustrate the W-shaped profile from either the horizontal or transversal section.

— Headbox for installation of pod unit. For open water scenarios, headbox may increase the appendage resistance and disturb the wake field, thus often minimized in design practice. However for stern-first icebreaking, headbox needs to serve two functions, i.e., providing a flat bottom for the integration of pod unit to ship hull and more importantly, acting like an ice horn (or ice cutter) to protect the pod from direct contact with intact ice. Moreover, a well-designed headbox may also promote the clearing of broken ice pieces to ship side.

Thus, for complex curved surfaces like the stern of a DAS, maintaining the original hull form can be difficult after a tactile sensor sheet is attached. Under such circumstances, alternative methods must be used.

Proposed methodology for testing stern-first ice resistance

As discussed above, although the "pre-sawn ice" or tactile sensors have been applied to obtaining the bow-first ice resistance, it is still necessary to seek alternative methods for the model testing of the stern-first ice resistance and its components. This alternative method needs to achieve the following objectives:

i. To measure the icebreaking resistance components separately and minimize the interference of the submersion resistance as much as possible;

ii. To analysis the influence of propeller speed on resistance components;

iii. To achieve the second objective, a pod unit must be incorporated, thus requiring independent measurement of the pod appendage resistance.

Based on the prior understanding of the mechanism and composition of stern-first ice resistance, the model tests are divided into four series. The specific testing principles, contents and logic are described as follows.

***Step 1**: Separate testing of* $R_{br}(0)$ *and* $R_{pod}(0)$

Considering that the icebreaking resistance is mainly generated by the stern area, a stern segment can be separately fabricated in the model design to conduct the independent measurement of the icebreaking resistance. As illustrated in Figure 5, the stern model is connected to the towing beam of the carriage with a load cell. Additionally, to measure the pod appendage resistance, model of the pod unit is separately connected to the towing beam through another load cell. There are small gaps between the stern model and pod model to avoid possible force transmission.

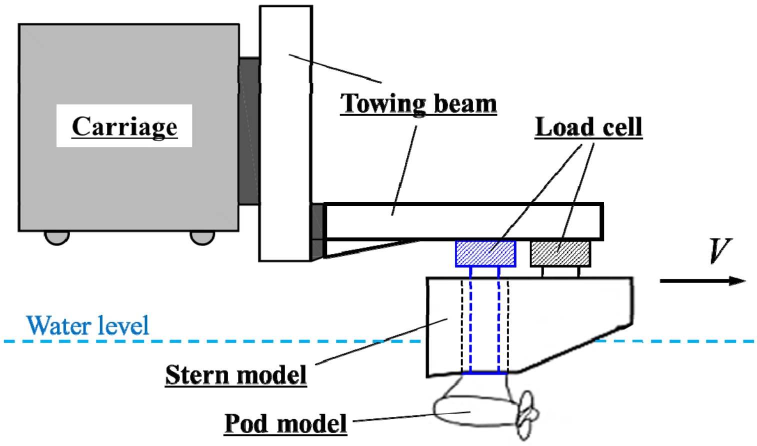


Figure 5. Model configuration for the separate measurements of $R_{br}(0)$ and $R_{pod}(0)$.

By conducting model tests under the condition of the propeller speed being zero and utilizing the test method illustrated in Figure 5, it is possible to achieve the testing and analysis of the stern icebreaking resistance $R_{br}(0)$ and the pod appendage resistance $R_{pod}(0)$ as described in Equation 3.

Step 2*: Separate testing of $R_{br}(n)$ and $R_{pod}(n)$*

Building upon the testing method depicted in Figure 5, by conducting tests at various propeller speeds, it is possible to measure the stern icebreaking resistance $R_{br}(n)$ and the pod appendage resistance $R_{pod}(n)$. When $n>0$, propeller thrust would act on the pod model, and thus the R_{pod} should be calculated by the sum of the measured tow force of the pod and the effective thrust. Note that the measured tow force of the pod can be negative when the thrust exceeds the ice resistance. Subsequently, by comparing these results with $R_{br}(0)$ and $R_{pod}(0)$ at zero propeller speed, the influence coefficients η_1 and η_3 can be calculated.

Step 3*: Towed propulsion tests of the entire ship to obtain $R(0)$ and $R(n)$*

Based on the testing of icebreaking and pod appendage resistance components, towed propulsion tests can be conducted with a fully equipped ship model (including the pod unit). By varying the propeller speed, the total resistance $R(0)$ at zero propeller speed and $R(n)$ under rotation can be obtained. The resistance under towed propulsion can be calculated by the sum of the tow force and effective thrust.

According to Equation 3, by subtracting the icebreaking and pod appendage resistance components from the total resistance, the submersion resistance $R_{sub}(0)$ under zero propeller speed, as well as the influence coefficient of rotation speed, i.e., η_2, can be obtained.

Step 4*: Another towed propulsion test for validation*

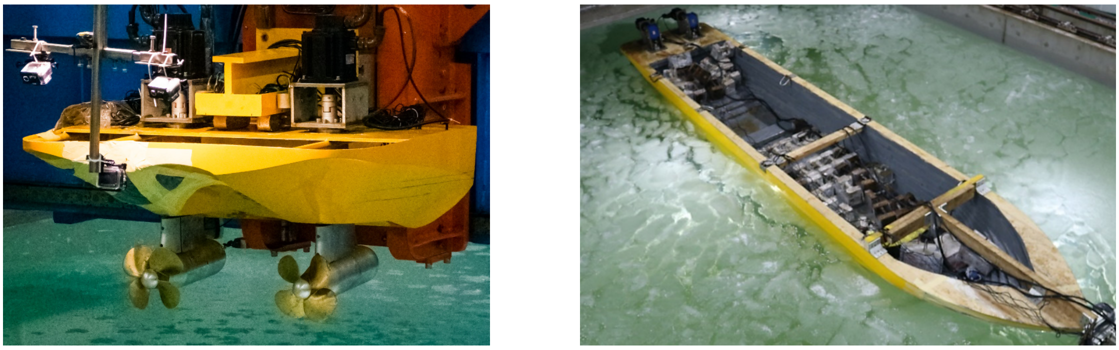
Following the above steps, it is possible to develop a semi-empirical calculation method for the ice resistance under stern-first mode. Still, it is necessary to validate the reliability of the calculation method by the results of a new series of model tests. Therefore, another series of towed propulsion tests need to be conducted. By comparing the calculated ice resistances with those predicted by the model tests, verification or improvement of the proposed calculation method can be made.

PRELIMINARY TESTS AND RESULTS

Test model and conditions

The Chinese polar research icebreaker *Xue Long 2* was selected to conduct the model test. Two podded propulsors are installed on this ship, with a propeller diameter of 4.25 m and rated rotation speed of 145 r/min in full scale. The icebreaking capability of this ship under stern-first mode is about 1.5 m of level ice with 20 cm snow under a speed of 2 knots and the maximum icebreaking capability in continuous motion about 1.8 – 1.9 m (Mattsson, 2016).

Following the test series mentioned above, a stern segment model, two pod models and a ship model were designed and fabricated for the present study, as shown in Figure 6. Since the stern segment is to measure the breaking resistance component, its longitudinal length was minimized to the "shoulder" of the stern to avoid the influence of submersion resistance as much as possible.



a) Stern and pod models b) Ship model equipped with two pod models

Figure 6. Models used for the present tests.

In preliminary tests, a full-scale ice thickness of 1.5 m was targeted. The ship velocity was selected to be 1.0 kn in full scale, and the ice flexural strength 650 kPa. Under the geometric scale factor of 1:20, the ice thickness in model scale was set to be 7.5 cm, the ship velocity 0.115 m/s, and the ice strength 32.5 kPa. Four propeller speeds were tested, including a zero speed and an over-load speed (i.e., higher than the rated rotation speed in model scale), according to the common practice from the propulsion tests in ice.

Test results

Model tests were conducted at the Ice Engineering Laboratory of Tianjin University, an ITTC member institution. Preliminary results of the resistance components under the above ice condition at stern-first mode are presented in Figure 7. The resistances have been converted to full scale according to the Froude-Cauchy similarities.

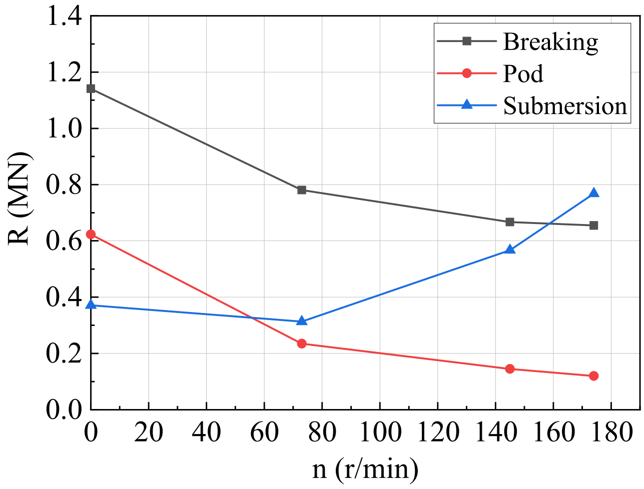
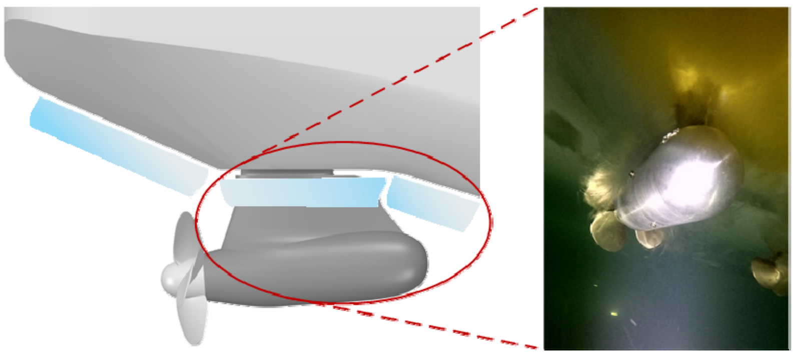
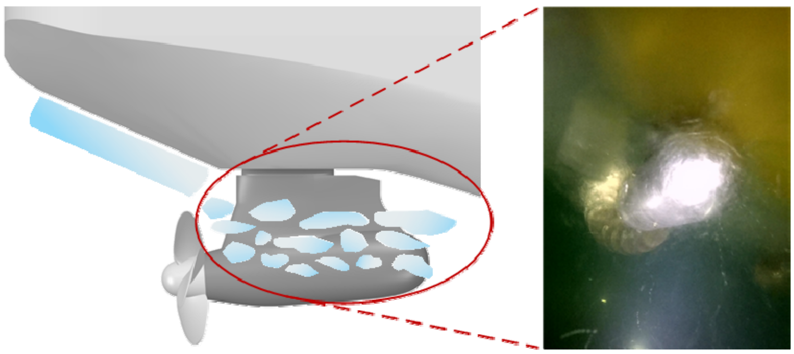


Figure 7. Preliminary results of the resistance components under stern-first mode.

As can be seen, propeller speed has different influences on the resistance components under stern-first mode. First, the icebreaking resistance decreases with the increase in propeller speed. Such result indicates that the suction effect caused by the rotating propellers could facilitate the bending failure of the ice sheet. Secondly, the pod appendage resistance decreases with the propeller speed. Such result could be attributed to the alteration of the ice failure mode in front of the pod unit. When the propeller speed is zero, the broken ice pieces slide along the hull and fails in crushing at the pod strut as illustrated in Figure 8a. While at medium or high rotation speed, the suction effect makes the ice pieces contact with the propeller blades and fail by milling as illustrated in Figure 8b.



a) at zero propeller speed



b) at medium or high propeller speed

Figure 8. Ice failure modes in front of the pod unit.

Thirdly, the submersion resistance shows an increasing trend with the propeller speed, which may result from the flushing effect by the propeller wake. As the ice pieces flows through the propeller disc, the propeller blades mill the ice into smaller fragments. These smaller ice fragments mix into the water flow and are rapidly cleared along the bottom and sides of the hull. Although it is difficult to quantify the ice coverage at the ship bottom under such condition, the ice flow attains a velocity significantly greater than the ship's speed due to the rotation of the propeller. Thus, the high-speed flushing by the ice flow to the ship hull may be the primary reason for the increase in submersion resistance at higher propeller speeds.

SUMMARY

In the present study, the ice resistance components of a double acting ship under stern-first mode are proposed. Influences of propeller speed on each component are considered and investigated by model tests.

To measure the resistance components separately, the present study proposed a four-step model testing methodology, which involves separate testing of stern segment icebreaking resistance and pod appendage resistance, testing under different propeller speeds, and towed propulsion tests of the entire ship. Preliminary results show that the breaking resistance and pod appendage resistance decrease with the increase in propeller speed, while the submersion resistance features an opposite trend.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (Grant Nos. 52192695, 52192691, 52192690 and 52101327), and the High-Tech Ship Projects of the Ministry of Industry and Information Technology of China (Grant No. 2021-342).

REFERENCES

Aker Arctic, 2016, First LNG icebreaker *Polaris*. Arctic Passion News No 12, Aker Arctic Technology Inc.

Appolonov E.M., Nesterov A.B., and Sazonov K.E., 2011, Regulation of extreme ice loads acting on hulls of azimuth propulsion systems for ice ships. Ships and Offshore Structures, 6(3): 239–247.

DNV, 2021, Ice strengthening of propulsion machinery and hull appendages. DNV-CG-0041, Class Guideline, Det Norske Veritas AS.

Enkvist E., 1983, A survey of experimental indications of the relation between the submersion and breaking components of level ice resistance to ships. Proceedings of 7th International Conference on Port and Ocean Engineering Under Arctic Conditions, pp. 484–493.

Huang Y., Huang S., Sun J., 2018, Experiments on navigating resistance of an icebreaker in snow covered level ice. Cold Regions Science and Technology, 152, 1–14.

ITTC, 2017, Resistance Tests in Ice. ITTC Recommended Procedures and Guidelines, International Towing Tank Conference.

Juurmaa K., Mattsson T., and Wilkman G., 2001, The development of the new double acting ships for ice operations. Proceedings of the International Conference on Port and Ocean Engineering Under Arctic Conditions, Ottawa, Canada.

Lindqvist, G., 1989, A straightforward method for calculation of ice resistance of ships. Proceedings of the 10th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Luleå, Sweden, pp. 722–735.

Mattsson, T.,2016. Operation Manual in Ice Area. Aker Arctic Technology Inc.

Sun J., Huang Y., 2023, Experimental Study on the Ice Resistance of a Naval Surface Ship with a Non-Icebreaking Bow. Journal of Marine Science and Engineering, 11(8), 1518.

Wilkman G., and Mattsson T., 2007, Double acting ships vs. ice bow. Recent Development of Offshore Engineering in Cold Regions, Yue (ed.), POAC-07, Dalian, China.