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Calculation of ice clearing resistance using normal vector of hull form and direct calculation of buoyancy force under the hull

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ABSTRACT: *The ice-resistance estimation technique for icebreaking ships had been studied intensively over recent years to meet the needs of designing Arctic vessels. Before testing in the ice model basin, the estimation of a ship's ice resistance with high reliability is very important to decide the delivered power necessary for level ice operation. The main idea of previous studies came from several empirical formulas, such as Poznyak and Ionov (1981), Enkvist (1972) and Shimansky (1938) methods, in which ice resistance components such as icebreaking, buoyancy and clearing resistances were represented by the integral equations along the Design Load Water Line (DLWL). The current study proposes a few modified methods not only considering the DLWL shape, but also the hull shape under the DLWL. In the proposed methodology, the DLWL shape for icebreaking resistance and the hull shape under the DLWL for buoyancy and clearing resistances can be directly considered in the calculation. Especially, when calculating clearing resistance, the flow pattern of ice particles under the DLWL of ship is assumed to be in accordance with the ice flow observed during ice model testing. This paper also deals with application examples for a few ship designs and its ice model testing programs at the AARC ice model basin. From the comparison of results of the model test and the estimation, the reliability of this estimation technique has been discussed.*

KEY WORDS: Ice; Resistance; Empirical formulas.

INTRODUCTION

The first Korean ice breaker was built and tested in the Arctic (Kim et al., 2011) and a number of projects related to the transportation of natural resources by icebreaking ships from or through the arctic region have been carried out recently, and a few of them are still under development stage.

Unlike normal ships operating in ice-free waters, for an icebreaking ship, the designers need to primarily consider the icebreaking capability of the ship and most importantly, designing a hull form of the ship. The hull-form design has been one of major parts of ice technology, and thereby, an estimation of the ice resistance is an important issue to both the shipbuilding companies and the researchers.

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The final goal of the ship designer is to find the optimum hull form for a given set of design parameters, such as the maximum engine size and capacity and target cargo capacity based on economic analysis.

During the concept and basic design stage, estimation of ice resistance induced by the hull form is an important step because it is the starting point of the calculation of the engine capacity.

For the estimation of ship resistance in ice, three methods are normally used, which are as follows:

1) Ice test in the ice model basin
2) Empirical formulas based on the parameters of a ship
3) Numerical simulation

Ice test in the ice model basin is the most reliable method to predict a ship's ice resistance as well as its powering performance in ice. However, the ice test is not a practical approach during the concept and the basic design stage because of the high cost and long testing time. Another alternative to this ice test is numerical simulation; however, such approach is still in its beginning stage. In this regard, empirical formulas based on the parameters of an icebreaking ship, thus seem to be a more practical and useful approach.

However, the empirical formulas may give large differences depending on the types and sizes of the ships because the published formulas used several parameters that were based on ice model test results for small sized icebreakers. Especially, for large cargo ships in the arctic region, the results of the empirical formulas are likely to show a larger difference than those of the ice model test.

To increase the reliability of the estimation scheme for large icebreaking ships, some useful published empirical formulas of Poznyak and Ionov (1981), Enkvist (1972) and Shimansky (1938) have been studied in this paper because those formulas were formulated reflecting the hull form geometry.

The ice resistance in most of the empirical formulas is generally comprised of three components, viz. icebreaking, buoyancy and clearing resistances, which are represented by the integral equations along the DLWL. In this regard, the current study proposes some modified methods considering not only the DLWL shape, but also the hull shape under the DLWL to increase the reliability of the ice resistance estimation.

The hull form of Double Acting Ships (DAS) can have either a "double V shape (VV)" or a "triple V shape (VVV)" in section of stern. To this V shapes, it becomes complicated to directly use any published formula because the integrand function diverges when clearing angle along the DLWL becomes close to 90 deg. To address this problem, a new way of calculation of the clearing resistance has been proposed in this study.

The current paper also deals with the application examples and its ice model testing programs at AARC ice model basin. From the comparison of results between the model test and theoretical estimation, the reliability of this estimation technique has been evaluated.

SCHEME FOR ICE RESISTANCE ESTIMATION

Definition of angles

The direction of x-axis is followed by length of ship from After Perpendicular (AP) to Fore Perpendicular (FP), the direction of y-axis is heading from center line to port side and the direction of z-axis is from bottom of ship to deck.

Fig. 1 shows definition of angles. Angle α is defined as the angle between the x-axis and the tangent of waterline at an arbitrary point in the x-y plane, angle β is the angle between the z-axis and the tangent of section line in the y-z plane and angle γ is the angle between z-axis and tangent line of buttock line in x-z plane. Vector $\vec{n}$ is the normal vector at an arbitrary point of hull form. Angle ϕ is the stem angle in profile view.

In case of 'double or triple V shape' for DAS, the geometry is divided into two or three parts, such as the inside and the outside to calculate the ice resistance separately, as shown in Fig. 2.

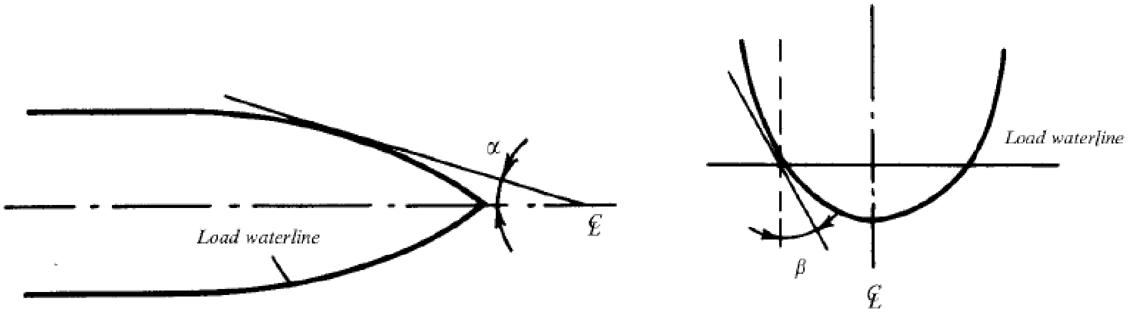
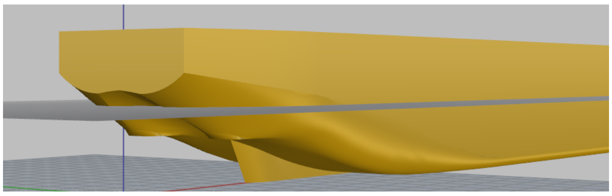


Fig. 1 Diagram of different angles.



↑ VV shape ↓ VVV shape

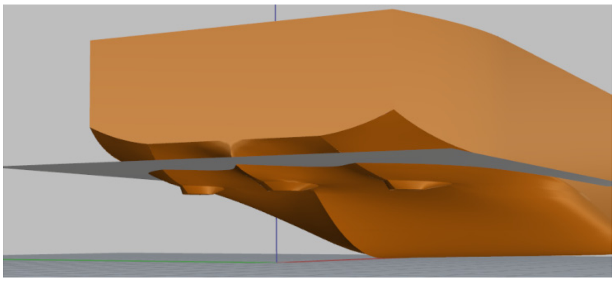


Fig. 2 Stern views of double or triple V shape.

Breaking resistance

Shimansky (1938) defined icebreaking parameter as F_Z / F_X, which means the ratio of the force induced by ice in *z* direction to that in *x* direction when a ship breaks the ice. Assuming a unit beam, the forces acting in *x*, *y*, *z* direction can be represented by Eqs. (1) to (3).

$$F_X = \int_0^{L_E} \frac{\tan^2\alpha\sqrt{1+\tan^2\alpha}}{1+\tan^2\alpha+\tan^2\beta}dx \tag{1}$$

$$F_Y = \int_0^{L_E} \frac{\tan\alpha\sqrt{1+\tan^2\alpha}}{1+\tan^2\alpha+\tan^2\beta}dx \tag{2}$$

$$F_Z = \int_0^{L_E} \frac{\tan\alpha\,\tan\beta\sqrt{1+\tan^2\alpha}}{1+\tan^2\alpha+\tan^2\beta}dx \tag{3}$$

where L_E is the entrance length between the fore end and the starting point of the parallel part of the bow-first icebreaking ship, as shown in Fig. 3.

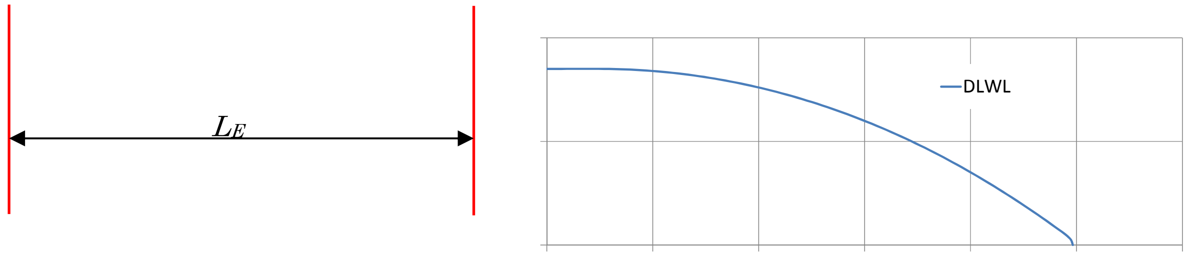


Fig. 3 The DLWL of icebreaking bow.

Additionally, the thrust is given by Eq. (4) for the unit beam.

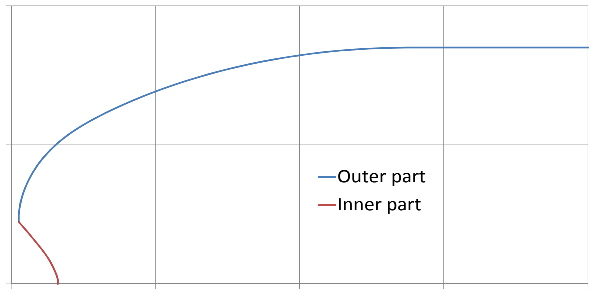
$$T = \frac{\lambda \sigma_f h^2}{1.93} \frac{F_X}{F_Z} \tag{4}$$

where

$$\lambda = \sqrt[4]{\frac{3\rho_w g}{Eh^3}} \tag{5}$$

In Eqs. (4) and (5), g is acceleration due to gravity, h is the thickness of the ice, E is the Young's modulus of the sea-ice and ρ_w is the density of water. Considering the breaking resistance for the unit breadth equal to the thrust in Eq. (4), the thrust multiplied by ship's own breadth is the total breaking resistance.

In case of 'double or triple V shape' for DAS, the calculations are carried out separately after dividing two or three parts of the DLWL according to an angle α of ±90°, as shown in Fig. 4, and the sum of all the two or three forces is the total breaking resistance of a ship.



↑ VV shape ↓ VVV shape

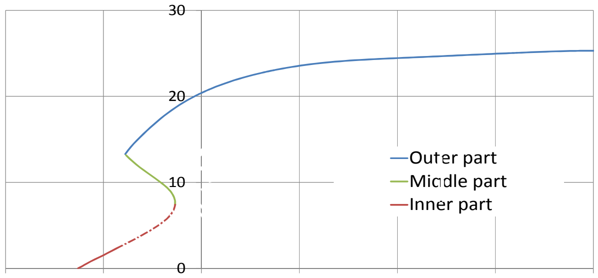


Fig. 4 The DLWL of double and triple V shape.

Clearing resistance

To know the clearing force, the Ionov method (Poznyak and Ionov, 1981) was used initially. Clearing resistance is a function of a ship's speed in ice and Ionov described the relations between the ship's speed, ice properties and geometry of the ship as shown in Eq. (6). Geometry of DLWL and some empirical coefficients were used in his formula. He assumed that clearing of ice happens only on the x-y plane along the DLWL.

$$R_{CI} = 2\rho_i h\sqrt{gB}\cdot V_S \begin{bmatrix} k_3' \int_0^{L/2} \dfrac{\left[y'(x)\right]^2}{\cos\alpha}dx \\ +k_3'' f_g \int_0^{L/2} \dfrac{y'(x)}{\cos\alpha}dx \end{bmatrix} \tag{6}$$

where V_S is the ship's speed, k_3' and k_3'' are empirical constants, f_g is the friction coefficient and ρ_i is the density of ice. However, the authors found out that Eq. (6) has certain irrational issues as follows:

1) The value of the integrand in Eq. (6) can be divergent when cos α goes to zero, especially at the end point of the DLWL of icebreaking bow. For DAS with double or triple V shape, the value of the integrand cannot also be determined when $y'(x)$ and cos α go to zero simultaneously, at the inflection point of the DLWL.
2) It is unrealistic to assume that the actual clearing of ice happens only according to the clearing angle α on the x-y plane along the DLWL. In addition, clearing of ice needs to be applied to both the hull form, surrounded by ice and under the DLWL, and the DLWL.

To solve the problems mentioned above, a new formula was proposed in this study by modifying the Ionov method and defining a more realistic clearing direction.

First, a more realistic clearing direction of broken ice can be defined by considering the geometrical analysis, shown in Fig. 5. A normal vector $\vec{n}$ at an arbitrary point on the hull surface is shown in Eq. (7). The vector $\vec{i}$ indicates the direction of the ship's progress. If we define the vector $\vec{p}$ as $\vec{i}\times\vec{n}$, the vector $\vec{p}$ is normal to the vector $\vec{n}$ and $\vec{p}$ as shown in Eq. (8).

$$\vec{n} = n_x\vec{i} + n_y\vec{j} + n_z\vec{k} \tag{7}$$

$$\vec{p} = \vec{i}\times\vec{n} = 0\vec{i} - n_z\vec{j} + n_y\vec{k} \tag{8}$$

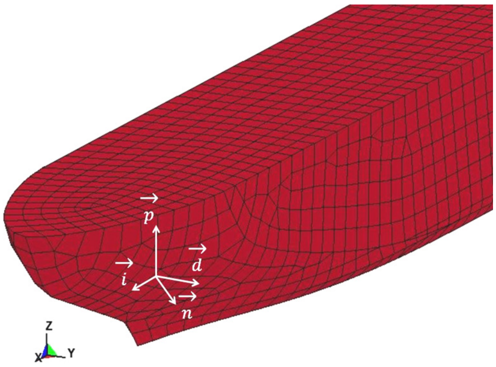


Fig. 5 Diagram of clearing plane.

When a curl calculation is done between $\vec{p}$ and $\vec{n}$ a new vector $\vec{d}$ is obtained, which is defined as a clearing direction of ice at an arbitrary point on the hull surface, surrounded by ice (Eq. (9)).

$$\vec{d} \approx \frac{\vec{p}\times\vec{n}}{\left|\vec{p}\times\vec{n}\right|} = \left(d_x,\, d_y,\, d_z\right) \tag{9}$$

To increase reliability in the calculation, a modified formula is shown in Eq. (10), which was obtained by considering the clearing of ice on both the x-y and the x-z planes.

$$R_{cl} = 2\rho_i h\sqrt{gB}\cdot V_S \times \left[\int_0^{L/2} \sqrt{y'(x)^2 + z'(x)^2}\,(k_3' + k_3'' f_g) n_x dx \right] \tag{10}$$

Finally, we assumed $y'(x) = d_y/d_x$ and $z'(x) = d_z/d_x$ to reflect the influence of a more realistic clearing direction. Then a new formula can be obtained, as shown Eq. (11).

$$R_{cl} = 2\rho_i h\sqrt{gB}\cdot V_S \times \left[\int_0^{L/2} \sqrt{(\frac{d_y}{d_x})^2 + (\frac{d_y}{d_x})^2}\,(k_3' + k_3'' f_g) n_x dx \right] \tag{11}$$

For a more exact calculation of the clearing resistance, it was assumed that the ice-covered area under the DLWL can be represented as four simple lines of ice flow, as shown in Fig. 6 in this study. To each of them was applied the line integral Eq. (11) and the average of four integration values gave the resultant clearing resistance.

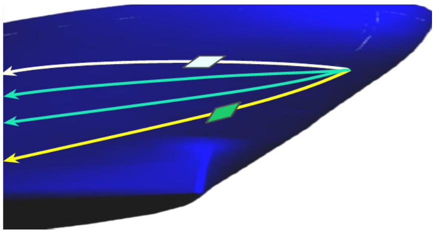


Fig. 6 Representation of the four lines of ice flow.

Buoyancy resistance

According to Enkvist (1938), buoyancy resistance can be divided into the pressure component induced by submerged ice in water, and the friction component caused by broken ice pieces. In the calculation of the buoyancy force, the geometry of the hull under the DLWL serves as important information. Enkvist assumed the geometry of hull to be covered with broken ice, and the length of the ice-covered hull surface is equal to half width of the ship, as shown in Fig. 7. The buoyancy resistance can be formulated, as shown in Eq. (12).

$$\begin{aligned} R_{Bu} &= \frac{\sum_0^{L/2} L_j \sum_0^B \rho_\Delta g h \bar{s} b_i}{L/2} \\ &+ \sum_0^{L/2} L_j \sum_0^B f_g \rho_\Delta g h b_i \sin\beta \end{aligned} \tag{12}$$

where b_i is a beam of ice piece in any section, L_i is the length between sections, ρ_Δ is the difference between the density of water and that of ice, and $\bar{s}$ is averaged depth of submergence.

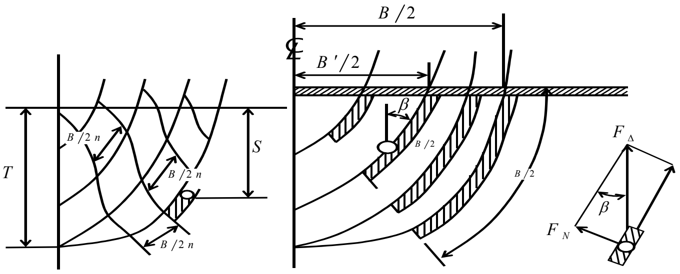


Fig. 7 Schematic diagram of buoyancy force acting on the hull surface.

EVALUATION OF THE ICE RESISTANCE ESTIMATION

To evaluate the reliability of the ice-resistance estimation, model test results of the designed hull form were compared with the calculated results. The designed hull form is for DAS, which has a traditional icebreaking bow and the icebreaking stern with triple V shape and 3 pods propulsion system, as shown in Fig. 2. Additionally, the principal dimension of the hull form is summarized in Table 1.

Table 1 Principal dimension of ship.

Items	Values
Length (*m*)	300.0
Breadth (*m*)	50.6
Design draft (*m*)	T_f / T_a = 11.7 / 11.7
Ballast draft (*m*)	T_f / T_a = 9.05 / 10.5

T_f : Draft at FP, T_a : Draft at AP

Model tests were carried out at the ice model basin of AARC. The speed performance tests through free running were carried out at 1.5 *m* level ice for design and ballast draft conditions in bow-first icebreaking (ahead mode). For stern-first icebreaking (astern mode), 1.5 *m* and 2.1 *m* level ice tests were carried out for design draft only. For all the tests, the flexural ice strength is 500 *kPa*.

Table 2 compares the calculated results and the model test results for the ahead mode, and Table 3 for the astern mode. The comparison results for both the ahead and the astern modes show that the difference is less than 5% for all speed at 1.5 *m* level of ice, but more than 10% at 2.1 *m* level of ice. Furthermore, the model test results and the calculated results according to the ship's speed change were also plotted (see Fig. 8). At 1.5 *m* level of ice, both the data shows a good agreement. Table 4 shows the ratio of each ice resistance component. The ratio depends on the vessel's speed, hull form and ice properties normally. Table 4 shows buoyance and clearing force is about 40% respectively in 1.5 *m* level ice, 500 *kPa* ice strength and 5 *knots*.

Table 2 Comparison of test results and estimation (ahead).

1.5 *m* level, 500 *kPa*	Vs (*knots*)	Ice resistance (*kN*)	
		Model test	Calculation
Ahead design	4.0	100	99.1
	5.0	100	93.9
Ahead ballast	3.0	100	99.2
	4.0	100	97.3
	5.0	100	95.2

Table 3 Comparison of test results and estimation (astern).

500 *kPa*, Design	Vs (*knots*)	Ice resistance (*kN*)	
		Model test	Calculation
1.5 *m* level Astern	3.0	100	101.2
	4.0	100	100.1
2.1 *m* level Astern	1.0	100	93.9
	2.0	100	88.7

Table 4 Ratio of ice component (ahead).

1.5 *m* level, 500 *kPa*	Vs (*kts*)	Ice resistance (%)			
		Breaking	Clearing	Buoyancy	Total
Ahead Design	3.0	22.5	28.5	49.0	100
	4.0	21.8	34.2	44.0	100
	5.0	21.1	38.9	40.0	100

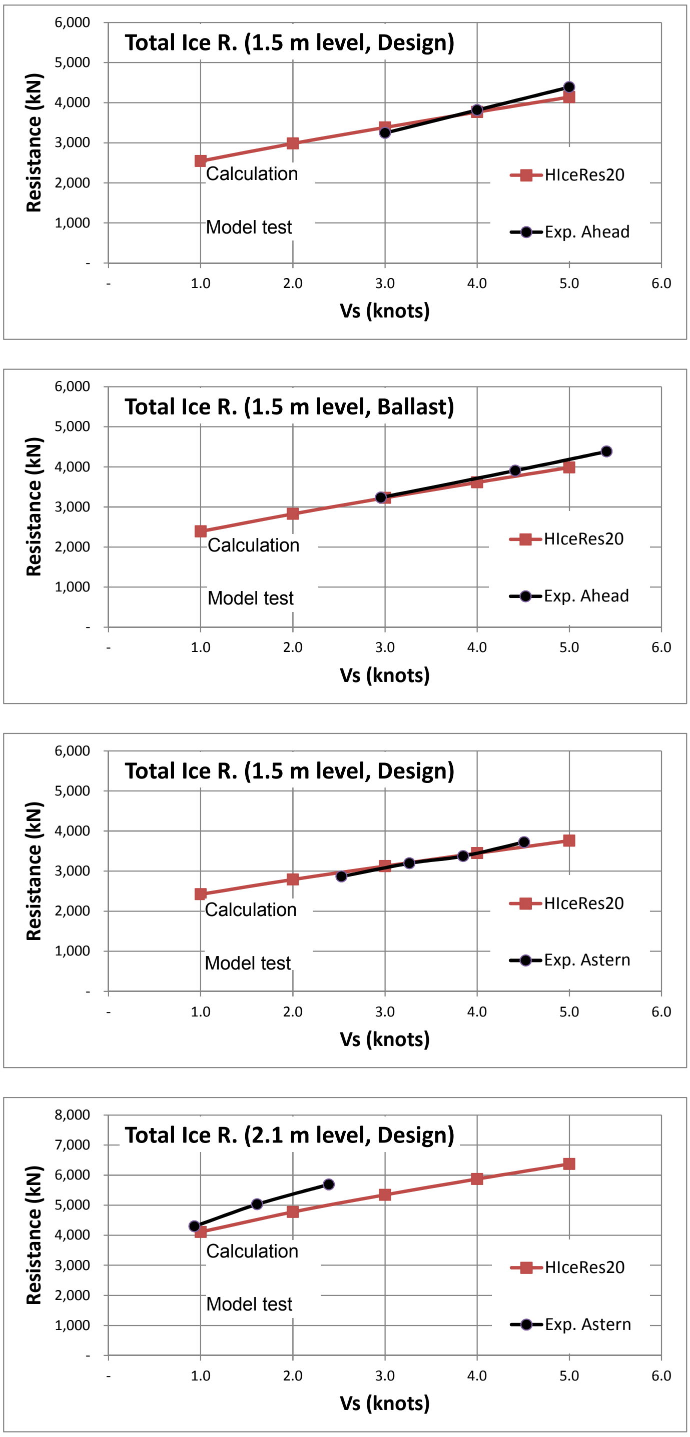


Fig. 8 Estimated ice resistance compared to the model test results.

Therefore, the current proposed method for the ice-resistance estimation can be utilized at the initial stage of a ship-design without wasting any time. Specifically, the proposed method in the present study will enable the ship designers to qualitatively evaluate a better hull form for ice performance or choose a design among many easily and quickly.

CONCLUSION

An estimation method for ice resistance was developed in this study and the results were compared with ice model test results. The Shimansky breaking resistance was applied using detailed hull geometry of the DLWL. To define a more realistic clearing direction and estimate the clearing resistance, a new formulation, modified from the Ionov method, was proposed. For buoyancy resistance, the Enkvist method was directly used.

The calculation results for large ice breaking ship with triple V shaped stern were compared to the model test results. The results show that, at 1.5 *m* ice thickness the difference between the calculated results and the model test results is less than 5%. The accuracy of the ice resistance estimation was verified so that the proposed method can be utilized in the initial design stage.

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