

Estimation of ice resistance and sensitivity analysis for an icebreaker

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Abstract The Lindqvist method is adopted to estimate the ice resistance for an icebreaker. The accuracy of the method is evaluated in a comparison of the calculated results with model test results. In addition to the estimation of ice resistance, a sensitivity analysis based on the Lindqvist method is carried out. A full parametric model developed using CAESES software allows the convenient construction of many new hull lines. The primary factors relevant to ice resistance are embedded as design parameters in the full parametric model. Meanwhile, response surface methodology is adopted to give better insight into new hull lines. Results show that the ice resistance is more sensitive to the rake angle and waterline entrance angle. The aim of the present study is to improve the techniques of designing the hull forms of icebreakers.

Keywords icebreaker, ice resistance estimation, sensitivity analysis, full parametric modeling, Lindqvist method, empirical formula

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1 Introduction

The extent of Arctic sea ice is decreasing gradually as global warming intensifies, opening up possible Arctic sea routes. The economic benefits of Arctic sea routes have promoted the development of icebreakers, with an increasing number of countries, including Russia and Finland, investigating icebreakers.

The early stage of design of an icebreaker relies to a large extent on the experience of designing previous icebreakers. The ice performance (i.e., the ice resistance and maneuverability) is one of the most important aspects of an icebreaker. However, the maneuverability of an icebreaker is too complex to predict and can only be evaluated in tests. There are therefore many empirical formulae for estimating

ice resistance in the development of icebreakers. Furthermore, the interaction between the ship hull and ice has been investigated (Riska, 2011) and it has been proposed that separate resistance components be studied separately. Most empirical formulae more or less consider the geometric features of the ship and the ice properties. Through long-term practice and experience, the hull lines of icebreakers have changed greatly. In particular, a spoon-shaped bow with a large waterline entrance angle has replaced a sharp bow (Sodhi, 1995).

Regardless of the benefits of using new Arctic sea routes, there has been insufficient research on icebreakers and especially on ice resistance. There is no set of standard, reliable or rapid prediction methods for investigating ice resistance internationally. It is thus necessary to develop a useful method of estimating the ice resistance in the early design stage.

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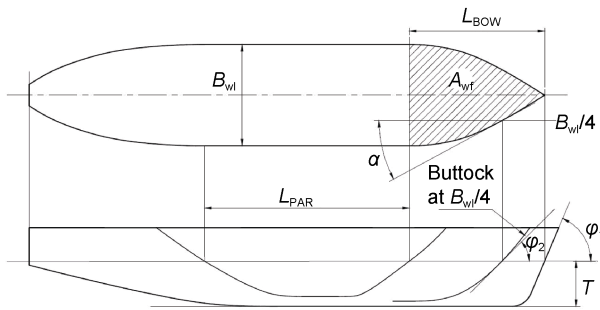


Figure 1 Geometric quantities of the hull.

Generally, ice resistance can be estimated using empirical formulae as mentioned above. However, the accuracy of the estimation strongly depends on the similarity between the target icebreaker and the database from which the empirical formulae were derived. The application conditions of each empirical formula are uncertain. Presently, the best way of estimating the resistance is to conduct ice model tests. However, considering the high cost of an ice model test, it is common for an empirical formula to be applied in the earliest stage of design of an icebreaker.

The present paper adopts the Lindqvist method (1989) to estimate ice resistance for an icebreaker. The accuracy of the method is evaluated by comparing calculation results with model test results. In addition to the estimation of ice resistance, a sensitivity analysis is performed using the Lindqvist method. A full parametric model developed using CAESES software allows the convenient construction of many new hull lines. The primary factors relevant to ice resistance are embedded as design parameters in the full parametric model. The geometric quantities of the hull are showed in Figure 1. Effects of the waterline entrance angle and rake angles of the stem at the centerline and $B_{wl}/4$ on the ice performance are investigated. Meanwhile, response surface methodology is adopted to obtain better insights into the performance of new hull lines. The aim of the study is to improve the techniques of designing the hull forms of icebreakers.

2 Full parametric modeling

A full parametric model for a polar vessel is constructed using the CAESES Friendship Framework (simply referred to as CAESES hereinafter), which is computer-aided design/computer-aided engineering software especially developed for geometric transformations. Many hull lines can be developed by establishing a partial or fully parametric model.

The main process is as follows. First, design parameters that are relevant to the ice resistance are determined and embedded in the full parametric model; e.g., the waterline entrance angle, the rake angles of the stem at the centerline and at $B_{wl}/4$, the length of the waterline and the ship beam. Second, longitudinal characteristic curves

that play the role of control lines are defined (Figure 2); e.g., the sectional area curve and center plane curve. Third, section curves are generated. Finally, the hull surface is constructed using a curve engine and metal surface function in CAESES. In this way, extensive parametric studies on the ice resistance can be undertaken for various icebreakers using many randomized created variants. The response surface methodology is used to gain better insights for different icebreakers with various parameters. Figure 3 shows a side view of the parametric model. This paper focuses on the bow shape and ignores the shape of the aft body.

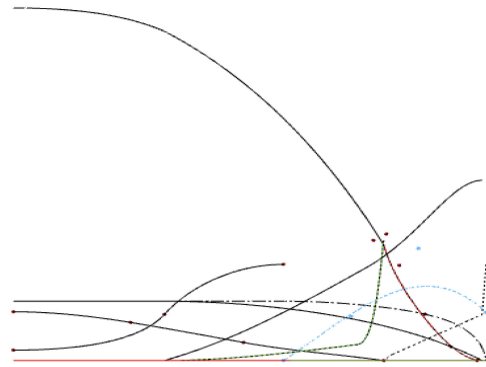


Figure 2 Characteristic curves used by CAESES to construct a full parametric model.



Figure 3 Side view of the parametric model constructed by CAESES.

3 Empirical prediction of ice resistance

3.1 Lindqvist method for predicting ice resistance

The Lindqvist method was proposed on the basis of the analysis of previous ice model test data and full-scale data. Lindqvist divided the resistance of an icebreaker into three components: R_B , R_C , and R_S . R_B denotes the resistance resulting from bending the ice sheet, R_C denotes the resistance resulting from crushing the ice sheet and R_S denotes the submergence resistance, relating to the friction force acting between the hull and ice floes and depending on the velocity of the icebreaker. These icebreaking components are analyzed separately. The components and overall resistance are expressed as equations (1)–(4).

$$R_C = 0.5\sigma_f H_i^2 \left(\tan \phi_1 + \mu \frac{\cos \phi_1}{\cos \Psi} \right) / \left(1 - \mu \frac{\sin \phi_1}{\cos \Psi} \right) \quad (1)$$

$$R_B = (37/64)\sigma_f B_{wl} \frac{H_i^{1.5}}{\sqrt{\frac{E}{12(1-\nu^2)\rho_w g}}} \left(\frac{\tan \Psi + \mu \cos \phi_1}{\cos \Psi \sin \alpha} \right) \left(1 + \frac{1}{\cos \Psi} \right) \quad (2)$$

$$R_S = (\rho_w - \rho_i)gH_i B \left[\frac{T(B+T)}{B+2T} + \mu(0.7L - \frac{T}{\tan \phi_1} - \frac{B}{4 \tan \alpha} + T \cos \phi_1 \cos \Psi \sqrt{\frac{1}{\sin^2 \phi_1} + \frac{1}{\tan^2 \alpha}} \right] \quad (3)$$

$$R_{ice} = (R_C + R_B)(1 + 1.4 \frac{V}{\sqrt{gH_i}}) + R_S(1 + 9.4 \frac{V}{\sqrt{gL}}) \quad (4)$$



Figure 4 Side view of the polar vessel.

The Lindqvist formula includes a wide range of ship form parameters and ice properties and considers the interaction between the ship and hull. The Lindqvist formula thus appears to give estimation results that are more reliable than those given by other empirical formulas. The use of empirical methods is limited in that the target ship must be similar to the ships used in creating the empirical formula.

3.2 Application of the Lindqvist method to an icebreaker

3.2.1 Icebreaker ship

The present paper takes a polar vessel constructed by Jiangnan Shipyard, China as a target icebreaker in evaluating the accuracy of the empirical formula. The side view of the polar vessel is shown in Figure 4. The ship was designed to achieve a speed of 2 n mile·h⁻¹ both ahead and astern at full power in level ice. It is considered that the level ice has a thickness of 1.5 m and is covered by a 20-cm layer of snow. The main particulars of the vessel are listed in Table 1.

3.2.2 Model tests

Several model tests were conducted in an ice tank to ensure the performance of the vessel navigating in level ice met requirements. The requirements for the performance at full power were a speed of 2 n mile·h⁻¹ both ahead and astern in level ice having a thickness of 1.5 m and a 20-cm snow layer. In theory, tests should be carried out for an ice thickness of 1.5 m and a 20-cm snow layer. However, the

Table 1 Main particulars of the ship and model

Symbol	Unit	Value
L_{oa}	m	121
L_{wl}	m	118
B_{wl}	m	21.5
T	m	7.5
φ	(°)	22
φ'	(°)	23
α	(°)	33
α'	(°)	59
ϕ_1	(°)	21
ϕ'_1	(°)	14

snow layer is typically modeled by increasing the thickness of level ice by one third of the thickness of the snow layer. The tests were therefore performed for the ice thickness of 1.57 m and 0.97 m. The model of the vessel was built to a scale of 1:22.764. Tests were conducted at three power levels in the experiment. The parameters measured during the ice model tests were the speed of the model and the rate of propeller revolution, from which the resistance due to ice can be defined through open-water overload calibration tests. In the model tests, the rate of propeller revolution was first set to a target value and the model was then allowed to

run freely. The model was free except for yaw and sway, which were restricted by guides to keep the model running straight. The test distance was long enough to allow the speed to settle and this constant speed was used in the analysis.

In terms of modeled ice properties, the Cauchy similarity criterion, proposed by Timco (1980), was adopted to maintain the similarity of Young's modulus between the prototype and model ice sheet. Table 2 gives the properties of the ice sheet, the value of thickness, flexural strength and Young's modulus will be measured to satisfy the requirement of model test.

3.2.3 Comparison of results between the empirical formula and model tests

The resistance calculated using the Lindqvist formula and the model test results are presented in Table 3.

Table 2 Properties of the ice sheet

	Symbol/Unit	H_i /m	σ_f /kPa	E /GPa
No.1	Prototype	1.57	500.8	8–9
	Model (Target value)	0.069	22	0.4–0.7
No.2	Prototype	0.97	500.8	8–9
	Model (Target value)	0.043	22	0.4–0.7

Table 3 Results of ice resistance

Ahead					Astern				
V	H_i	Rice_Exp.	Rice_Cal.	Error/%	V	H_i	Rice_Exp.	Rice_Cal.	Error/%
1.92	1.59	1622	1599.1	1.41	1.15	1.71	1311	1567.3	19.55
1.45	1.62	1445	1429.0	1.11	0.86	1.68	1217	1370.2	12.59
0.72	1.65	1198	1223.9	2.16	0.55	1.75	1061	1343.3	26.61
3.77	0.95	1270	1250.6	1.53	3.58	0.91	1107	1155.7	4.4
3.21	0.95	1141	1145.7	0.41	3.21	0.89	1011	967.3	-4.32
2.51	0.95	926	1014.5	9.56	2.01	0.91	819	807.9	1.36

It is noted that Young's modulus measured in the experiment is not used in the Lindqvist formula. This is because the real-scale Young's modulus derived from measurements in the model tests is much smaller than the conversional values adopted in previous research. More specifically, Young's modulus for the prototype of the ice model is about 0.4–0.7 GPa whereas previous research typically found values of Young's modulus of about 8–9 GPa (Ren and Zou, 2016). The reason for such a large difference may be the measurement method used in the tests. There are two methods of measuring Young's modulus. One is a static measurement while the other is a dynamic measurement. The result of a static measurement is always in the range of 0.3–10 GPa while that of a dynamic measurement is about 6–10 GPa (Wang and Shen, 2016). The small measurement results of the present model tests indicate that a static measurement was made. However, the principle of static measurement is that the deformation is measured after loading. There is enough time for viscoplastic deformation and elasto-brittle deformation to occur. The static measurement therefore measures the total deformation and it does not consider continuous creep deformation or elastic deformation. The present paper therefore abandons the idea of obtaining Young's modulus from the measurements.

The relationship between Young's modulus and flexural strength is given as equations (7) (Langleben and Pounder, 1961). Table 4 gives Young's modulus calculated from the flexural strength measured in the model tests.

$$\sigma_f = 1.76 \times e^{-5.88 \times \sqrt{V_b}} \quad (5)$$

Table 4 Calculation results for Young's modulus

No.	f_{model} /kPa	$f_{\text{prototype}}$ /MPa	E /GPa
1	22.3	0.51	9.76975
2	20.3	0.46	9.76687
3	19.8	0.45	9.76610
4	27.3	0.62	9.77590
5	25.3	0.58	9.77360
6	23	0.52	9.77070
7	23.1	0.53	9.77083
8	29.75	0.68	9.77848
9	23.30	0.53	9.77109

$$E = 10 - 0.0351 \times V_b \quad (6)$$

$$\sigma_f = 1.76 \times e^{-5.88 \times \sqrt{\frac{10-E}{0.0351}}} \quad (7)$$

In addition, the density of ice is $900 \text{ kg} \cdot \text{m}^{-3}$, Poisson's ratio is 0.3 and the frictional coefficient is 0.1 in this paper.

The experimental results show that, for similar ice properties, the resistance is in direct proportion to the velocity and ice thickness. This finding aligns with common sense and the results calculated using the Lindqvist formula. The experimental results show that the ice resistance for going astern is lower than that for going ahead when the velocity is similar. The main difference between going ahead and going astern in the resistance calculation using the Lindqvist formula is the angle of the waterline. A large

angle of the waterline pushes the ice floes aside instead of pushing the floes to the ship bottom. This would lead to a weaker friction force. At the same time, it is obvious that the accuracy of the Lindqvist formula is high for going ahead. It is concluded that the Lindqvist formula is not suitable for estimating the resistance when a ship has a large waterline entrance angle.

4 Results and discussion

4.1 Results of sensitivity analysis

Table 3 shows that the Lindqvist formula provides more reliable results for a thinner ice sheet ahead. On this basis, a sensitivity analysis is carried out to investigate the effects of variable geometric parameters on the estimated ice resistance. The ice properties and vessel velocity are kept the same during the study. The geometrical shape of the polar vessel is set as a basic model. The resistance of the vessel navigating ice with thickness of 1.62 m ahead at a speed of $1.45 \text{ m}\cdot\text{s}^{-1}$ is taken as a reference point. Parameters with an asterisk in Table 1 are considered variables.

4.1.1 Effects of the waterline entrance angle

Because the Lindqvist method produces invalid results for a ship with a large waterline entrance angle, the range of the angle is no more than 50 degrees in this analysis. The three components of resistance proposed by Lindqvist are calculated separately. The results of the calculation are presented in Figure 5.

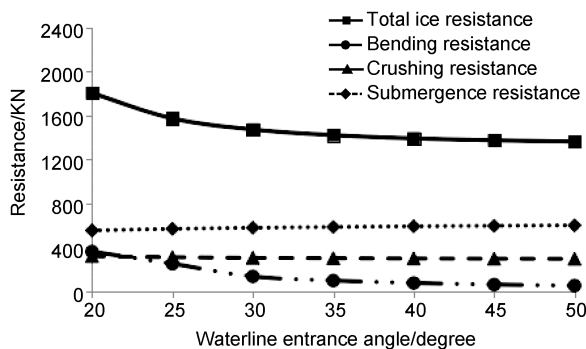


Figure 5 Effects of the waterline entrance angle on resistance.

Figure 5 clearly shows that the total ice resistance decreases as the waterline entrance angle increases. In particular, the total resistance decreases rapidly in the range of 20 to 35 degrees. The figure shows that the waterline entrance angle strongly affects the bending resistance but not the crushing and submergence resistance. This suggests that a larger waterline entrance angle avoids bending of the ice sheet.

4.1.2 Effects of the rake angle of the stem at the centerline

The rake angle of the stem at the centerline ranges from 20

to 50 degrees in this study. Results obtained using the Lindqvist method for different rake angles are presented in Figure 6.

The results show that the total ice resistance increases with the rake angle of the stem at the centerline; i.e., a smaller rake angle of the stem benefits the ice resistance. The crushing resistance is more sensitive than the bending resistance and submergence resistance to the rake angle. This suggests that a smaller rake angle of the stem at the centerline allows the ship to better slide on the ice sheet rather than crush the ice sheet directly. The total resistance is more sensitive to the rake angle than the waterline entrance angle.

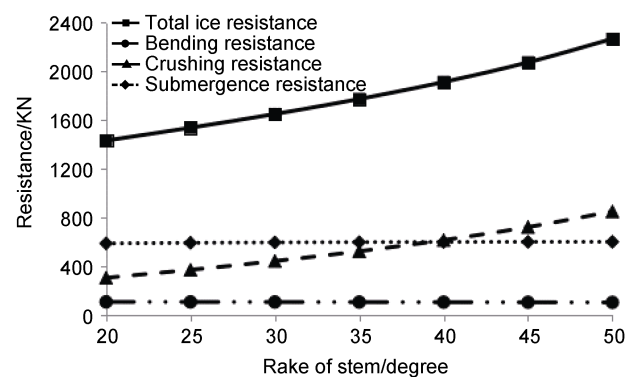


Figure 6 Effects of the rake angle (centerline) on resistance.

4.1.3 Effects of the rake angle of the stem at $B_{wl}/4$

Similar to the rake angle of the stem at the centerline, the rake angle at $B_{wl}/4$ is limited to the range of 20–50 degrees. An increasing rake angle at $B_{wl}/4$ increases the total ice resistance, just like the rake angle at the centerline as showed in Figure 7. However, the buttock angle at $B_{wl}/4$ strongly affects the bending resistance rather than the crushing resistance or submergence resistance. Additionally, an increase in the rake angle at $B_{wl}/4$ reduces submergence. This may be explained by the large rake angle at $B_{wl}/4$ being beneficial in terms of pushing the broken ice floes away. However, this suggestion should be verified further.

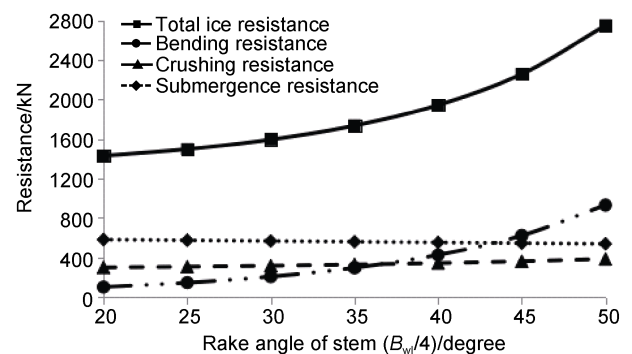


Figure 7 Effects of the rake angle ($B_{wl}/4$) on resistance.

4.2 Combination of different design parameters

According to the previous discussion, a larger waterline entrance angle together with smaller rake angles at the centerline and $B_{wl}/4$ will result in lower ice resistance. Recall that the conclusion is valid under the assumption that the ice properties and ship velocity are the same. However, the desirable bow ship is not a superposition of a larger waterline entrance angle with smaller rake angles at the centerline and $B_{wl}/4$. The reason is twofold. First, the flare angle can be determined by the waterline angle and the rake angle of the stem at $B_{wl}/4$. A change to the waterline entrance angle or the rake angle of the stem at $B_{wl}/4$ must affect the flare angle. This is to say, some parameters are not independent and should be considered together. Second, a different parameter value may lead to a different bow shape. Some values may be abnormal and should be excluded. Furthermore, in addition to the parameters above, the breadth of the ship and the flare angle also affect the ice resistance. At the preliminary design stage, the ship hull, especially the bow shape, could be a combination of these parameters. Different bow shapes based on many randomized variants can be viewed in CAESSES. Using an optimization algorithm, a desirable bow shape with low ice resistance could be obtained. Additionally, it is easy to eliminate an abnormal bow shape.

5 Conclusion

The ice resistance is one of the most important aspects of an icebreaker in the early design stage. The aim of the present study could be used to improve the techniques of designing the hull forms of icebreakers. All conclusions could be listed as followed.

(1) The results of estimating resistance using the Lindqvist method may be reliable for some types of ship. The accuracy may be related to the waterline entrance angle, as was discussed in section 3.2.3. It is suggested that the Lindqvist method is applicable to ships with a small waterline entrance angle. The application conditions of the Lindqvist method should be further studied.

(2) The waterline entrance angle has negative correlation with the estimated resistance. The total ice resistance decreases as the waterline entrance angle increases. More specifically, an increase in the waterline entrance angle reduces the bending resistance.

(3) The crushing resistance is more sensitive to the rake angle at the centerline. There is positive correlation between the crushing resistance and rake angle. This can be explained by a small rake angle at the centerline making it easy for the icebreaker to slide on the ice sheet and break the ice sheet from the top with its weight. The crushing resistance could thus be reduced. According to the Lindqvist method, the rake angle has little effect on the other two components of resistance. The total resistance would thus be small corresponding with a small rake angle

at the centerline.

(4) An increase in the rake angle at $B_{wl}/4$ increases the total resistance. In particular, an increase in the rake angle at $B_{wl}/4$ increases the bending resistance and decreases the submergence resistance. The reason may be that a large rake angle at $B_{wl}/4$ is helpful in terms of pushing away broken ice floes and thus reducing the friction force action between the ice floes and the ship hull. However, this suggestion should be verified further.

(5) The full parametric model is convenient to use in constructing different ship hulls with different geometric parameters, especially the bow shape. Using an optimization algorithm, a desirable ship hull that has low estimated resistance can be obtained by changing the design variables.

An empirical formula can be used to estimate ice resistance in the preliminary design stage of an icebreaker. The accuracy of the estimation depends on the similarity between the target ship and the ships in the database from which the formula is derived. However, the use of an empirical formula cannot replace model tests in terms of providing accurate results. Meanwhile, the application conditions of the empirical formula should be studied further.

Nomenclature

L_{oa}	Length overall, m
L_{wl}	Length of the waterline, m
B_{wl}	Maximum breadth of the ship, m
T	Draught of the ship in an ice region, m
A_{wf}	Area of the waterline of the bow, m^2
φ	Rake angle of the bow at the centerline, degrees
φ'	Rake angle of the stern at the centerline, degrees
α	Waterline entrance angle at $B_{wl}/4$ (fore body), degrees
α'	Waterline entrance angle at $B_{wl}/4$ (aft body), degrees
φ_1	Rake angle of the bow at $B_{wl}/4$, degrees
φ'_1	Rake angle of the stern at $B_{wl}/4$, degrees
H_i	Thickness of the ice sheet, m
E	Young's modulus, Pa
σ_f	Flexural strength, Pa
V_b	Volume of saltwater
V	Ship speed, $m \cdot s^{-1}$
ψ	Flare angle $\psi = \arctan \frac{\tan \varphi_1}{\sin \alpha}$, degrees
ρ_w	Density of seawater, $kg \cdot m^{-3}$
ρ_i	Density of ice, $kg \cdot m^{-3}$
μ	Frictional coefficient
ν	Poisson ratio

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