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Influence of Bow Design on Ice Resistance for Arctic LNG Carriers

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Abstract: In order to understand the influence of bow shape on ice resistance and provide guidelines for hull line design in the early design stage, an investigation of the impact of bow shape on ice resistance for the Arctic LNG carriers is carried out based on semi-empirical methods. Firstly, some typical semi-empirical formulas developed for ice resistance estimation of cargo carriers in different ice conditions are summarized. Then, formulas appropriate for ice resistance estimation of Arctic LNG carriers under different ice conditions are verified according to the result comparison between semi-empirical formulas and experimental tests. The comparison result indicates that the Lindqvist formula is appropriate for ice resistance estimation in level ice conditions, Zuev and Dobrodeev formula for ice resistance estimation in broken ice conditions, and Dobrodeev formula for ice resistance estimation in brash ice conditions. After that, the parameters considered in the selected formulas are summarized, and the influence of critical parameters on ice resistance is analyzed. Some parameters describing the ship's bow shape characteristic like ship breadth, waterline angle and stem angle greatly influence the ice resistance. Ice resistance increases with both the growth of ship breadth under all ice conditions and the growth of stem angle in level ice and broken ice conditions while ice resistance decreases with the development of waterline angle under all ice conditions. Finally, the optimization of the bow shape is discussed, and an optimized bow shape with both a large waterline angle and low stem angle is proposed. The optimized bow shape can decrease ice resistance by 9.9% in the level ice condition and reduce ice resistance by 11.3% in the brash ice condition.

Key words: Arctic LNG carrier; ice resistance; level ice; brash ice; broken ice; semi-empirical formula

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0 Introduction

The world's continuous demand for natural resources has led to an increasing interest in developing Arctic natural gas resources, and many LNG plants have been invested in the past years[1]. But the remote locations of the above LNG plants and the severe natural environment is a tremendous challenge for LNG transportation. However, regional climate change and Arctic ice melting increase maritime activity opportunities in historically inaccessible areas[2]. The Northern Sea Route

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(NSR) offers a very competitive shipping route to destinations in Asia. An Arctic LNG carrier can transport natural gas from Russia′s ports to the markets in eastern Asia via NSR[3-4].

Arctic LNG carriers are a newly-developed type of ice-going cargo ships. In addition to the conventional LNG carrier design requirements, they have some other design challenges considering the unique characteristic of the Arctic area. The hull line should be optimized to balance the performance in both open water and ice-going conditions[5]. In the design stage, accurate assessment of ice loads on the hull structure and prediction of the ship′s ice-going performance is critical, which will help designers to determine the hull form and select the economic propulsion system.

At present, the evaluation of ice resistance mainly consits of ice model tests[6-7], numerical simulation[8-9] and semi-empirical methods[10]. In a practical ship design, semi-empirical methods are adopted to approximately predict ice resistance in the early design stage. A numerical simulation may be used after development of one or more potential plans. But up to now, the numerical simulation is not sufficiently reliable to give a valuable contribution to the design process[11]. Thus, in the later design stage, ice model tests have to be used to evaluate one or a few specific designs. The final design is also verified and confirmed through ice model tests.

Considering the high expense and time consumption of ice model tests, it is advantageous to evaluate the ice resistance of a vessel in an early design stage as precisely as possible. Many semi-empirical formulas have been developed to calculate ice resistance for different ice-breaking conditions[12-13]. But all those semi-empirical models are created for a certain kind of ship or even a specific type of ice condition. The estimation errors may be caused if the formulas are misused. So, the applicability of the semi-empirical formulas for Arctic LNG carriers should be investigated[14]. Besides, most formulas focus on resistance prediction in level ice conditions, and few examine ice resistance in brash and broken ice conditions. As a merchant ship, when sailing in the Arctic, the ship encounters not only level ice but also brash or broken ice. Estimating the ice resistance of the cargo carrier under different ice conditions is essential, so formulas appropriate for the ice resistance of the LNG carrier under multiple ice conditions are necessary. Based on the proper formulas, it is possible to understand the influence of bow shape on the ice resistance and help optimize the hull form in the early design stage.

This study aims to identify proper semi-formulas for ice resistance of the Arctic LNG carriers and investigate the influence of bow shape on ice resistance to help improve hull line design efficiency in the early stage. The paper is outlined as follows. Some typical semi-empirical formulas developed for ice resistance estimation of cargo carriers in different ice conditions are summarized in Chapter 1. In Chapter 2, formulas appropriate for ice resistance estimation of Arctic LNG carriers are verified according to ice resistance result comparison between semi-empirical formulas and experimental tests. In Chapter 3, parameters considered in the selected formulas are summarized, and the influence of the critical parameters describing bow shape on ice resistance is analyzed. After that, the optimization of the bow shape is discussed, optimized bow shape with a larger waterline angle and low stem angle is suggested in Chapter 4. The main conclusions of the paper are presented in Chapter 5.

1 Semi-empirical formulas for ice resistance estimation

1.1 Level ice condition

As for empirical formulas for level ice resistance estimation, many semi-empirical formulas have been developed. Those formulas show significant discrepancies when applied to the same ship and compared to one another[13]. Hu and Zhou[15] calculated the ice resistance of an ice-breaking oil tanker in level ice conditions with some empirical formulas and compared it with the experimental result. It is found that the Lindqvist formula[16] and Jeong formula[17] agree well with the experimental result. As both belong to the ice-going cargo vessel, the hull form of an LNG carrier is relatively similar to that of an ice-breaking tanker. So, the above two formulas are also selected for ice comparison.

(1) Lindqvist formula

The Lindqvist formula is based on full-scale experimental data for a broad range of ship sizes and various parameters considered of influencing ice resistance. This model divides ice resistance into crushing, bending and submergence. The formulas are expressed as follows:

$$R_{\mathrm{ice}} = \left(R_{\mathrm{c}} + R_{\mathrm{b}}\right)\left(1 + 1.4\frac{V}{\sqrt{gh_{\mathrm{i}}}}\right) + R_{\mathrm{s}}\left(1 + 9.4\frac{V}{\sqrt{gL}}\right) \tag{1}$$

$$R_C = 0.5\sigma_{\mathrm{f}}h_{\mathrm{i}}^2 \cdot \frac{\tan\varphi + f\cdot\cos\varphi/\cos\psi}{1 - f\cdot\sin\varphi/\cos\psi} \tag{2}$$

$$R_{\mathrm{b}} = \frac{27}{64}\sigma_{\mathrm{f}}B\sqrt{\frac{12h_{\mathrm{i}}^3\left(1-\nu^2\right)g\rho_{\mathrm{w}}}{E}} \cdot \frac{\tan\psi + f\cos\varphi}{\cos\psi\sin\alpha} \cdot \left(1 + \frac{1}{\cos\psi}\right) \tag{3}$$

$$R_{\mathrm{s}} = \left(\rho_{\mathrm{w}} - \rho_{\mathrm{i}}\right)gh_{\mathrm{i}}B\left(T\frac{B+T}{B+2T} + k\right) \tag{4}$$

$$k = f\left(0.7L - \frac{T}{\tan\varphi} - \frac{B}{4\tan\alpha} + T\cos\varphi\cos\psi\sqrt{\frac{1}{\sin\varphi^2} + \frac{1}{\tan\alpha^2}}\right) \tag{5}$$

$$\psi = \arctan\left(\frac{\tan\varphi}{\sin\alpha}\right) \tag{6}$$

where, σ_{f} is flexural strength of the ice, taken as 500 kPa; E is the Young modulus of the level ice, taken as 2.0E9 Pa; ν is the Poisson ratio of the level ice, taken as 0.3; h_{i} is the thickness of ice; L, B, T are respectively length, breadth and draught of the ship, values of these variables are listed in Tab.2; ρ_{w}, ρ_{i} are respectively density of seawater and ice, taken as 1030 and 900 kg/m^3; α is waterline angle, taken as 39°; φ is stem angle, taken as 32°; f is friction factor of ice-hull interaction, taken as 0.08; and g is the acceleration of gravity, taken as 9.8 m/s^2.

(2) Jeong formula

The Jeong formula for level ice resistance estimation is applied for the standard icebreaker model using a component method of ice resistance. In this formula, ice resistance is calculated as follows:

$$R_{\mathrm{ice}} = 13.14V^2 + C_{\mathrm{B}}\Delta\rho gh_{\mathrm{i}}BT + C_{\mathrm{c}}F_{\mathrm{h}}^{-a}\rho_{\mathrm{i}}Bh_{\mathrm{i}}V^2 + C_{\mathrm{BR}}S_N^{-b}\rho_{\mathrm{i}}Bh_{\mathrm{i}}V^2 \tag{7}$$

$$F_h = \frac{V}{\sqrt{gh_i}} \tag{8}$$

$$S_N = \sqrt{\frac{B \cdot V^2 \cdot \rho_i}{\sigma_f h_i}} \tag{9}$$

where, C_B, C_c and C_{BR} are coefficient of ice buoyancy resistance, coefficient of ice clearing resistance,and coefficient of ice breaking resistance respectively ;a is the index of Froude number; b is the index of strength number; the value of those coefficients are shown in Tab. 1, and $\Delta\rho$ is water density minus ice density, taken as 130 kg/m^3.

Tab.1 Coefficients of Jeong formula for level ice resistance

Symbol	C_B	C_C	C_{BR}	a	b
value	0.5	1.11	2.73	1.157	1.54

1.2 Broken ice condition

Performance in broken ice conditions is vital for an ice-going cargo vessel because it usually follows a sea path covered with broken ice opened by an icebreaker. In contrast to the fact that many semi-empirical formulas have been presented for ice resistance estimation in level ice conditions, limited formulas have been developed for ice resistance calculation in broken ice conditions. Two semi-empirical formulas available for ice calculation in broken ice conditions are presented as follows:

(1) Zuev and Dobrodeev formula

This formula was first developed by Russian researcher Zuev[18], which is used for estimating the propulsion performance of cargo carriers in channels with broken ice, and the formula is suggested as follows:

$$R_{ice} = 0.63\frac{\rho_i g B h_i^2}{\left(B_c/B\right)^{3/4}}\left(0.13\frac{B}{h_i} + 1.3F_h + 0.5{F_h}^2\right)s^2(2 - s) \tag{10}$$

Dobrodeev[19] pointed out that the Zuev formula does not consider the fore hull shape. So, the above formula was modified considering specific hull form features such as different stem and waterline slope angles. The revised formula is as follows:

$$R_{ice} = 0.63\frac{\rho_i g B h_i^2}{\left(B_c/B\right)^{3/4}}\left(0.13\frac{B}{h_i} + 1.3F_h + 0.5{F_h}^2\right)s^2(2 - s)/\left(1 - \left(0.17 - 0.58\psi + 0.66\psi^2\right)\right) \tag{11}$$

where, B_C is the width of the ice channel, taken as 1.2 times of ship breadth; s is ice concentration, taken as 0.8; F_h is Froude number depending on ice thickness, which has been defined in Eq.(8); ψ is hull flare angle, which has been described in Eq.(6).

(2) Woolgar & Colbourne formula

Woolgara & Coulbourne[20] investigated the relationships between the pack ice force of offshore vessels and the key variables such as hull-ice friction. Then a modified formulation was developed for pack ice resistance prediction, including hull-ice friction coefficient, ice floe size and ice concentration. The equation used for pack ice is expressed as follows:

$$R_{ice} = 0.5C_P\rho_i Bh_i V^2 \tag{12}$$

$$C_P = 10^{2.302}\left(F_h\right)^{-1.173} f^{0.265}\left(\frac{d_{floe}}{B}\right)^{0.898} s^{5.88} \tag{13}$$

where d_{floe} is the size of ice floes, taken as 10 m.

1.3 Brash ice condition

Brash ice is the accumulation of floating ice made up of fragments not more than 2 m across and is the wreckage of other ice forms. Navigating in the brash ice channels is the most common mode for commercial vessels, and they only need to navigate in the existing old route filled with ice wreckages. But investigation of ice resistance of ships sailing in brash ice channels has been reported in limited publications. This part presents two empirical formulas for brash ice resistance estimation.

(1) Dobrodeev formula

Dobrodeev et al[21] presented a formula for estimating brash ice resistance. In this formula, ice resistance is divided into four components: resistance due to brash ice displacement by the ship hull over a distance equal to ship draught, momentum resistance due to some instant velocity of brash ice particles impacted by the ship hull, resistance due to friction of brash ice particles against ship bow, and resistance due to conflict of brash ice particles against ship's side. The ice resistance is calculated as follows:

$$\begin{aligned} R_{ice} = {} & \Delta\rho(1-n)gTh_i\frac{B}{2\sin\alpha}\left[1+\frac{1}{\sin\alpha}\left(1-\frac{2T}{B}\right)\right]+\rho_i(1-n)\frac{B}{2\sin\alpha}h_i V^2\left(\frac{1}{\sin\alpha}+\frac{1}{\sin\varphi}\right)^2+ \\ & f\Delta\rho(1-n)gh_i\frac{(B-2T)}{\sin\alpha}\left[L_{PM}-\frac{V_{bott}\sin\alpha}{B-2T}+\frac{T\cos\theta}{\tan\varphi}\right]+2f\Delta\rho(1-n)gS_{PM}L_{PM}\frac{\sin\chi\cos\gamma}{\cos(\chi+\gamma)} \end{aligned} \tag{14}$$

$$V_{bott} = L_{PM}\left(h_i-\frac{B-2T}{8\sin\alpha}\tan\chi\right)\left(\frac{B-2T}{4\sin\alpha}\right) \quad \text{if } \left(\frac{B-2T}{8\sin\alpha}\right)\tan\chi < h_i \tag{15}$$

$$V_{bott} = \frac{L_{PM}h_i^2}{2\tan\chi} \quad \text{if } \left(\frac{B-2T}{8\sin\alpha}\right)\tan\chi \geqslant h_i \tag{16}$$

$$\theta = \arcsin\left(1-\frac{\cos^2\alpha}{\cos^2\varphi}\right)^{0.5} \tag{17}$$

$$\gamma = \arctan f_{ii} \tag{18}$$

where, χ is the natural slope of the brash ice channel, taken as 4°; n is brash ice porosity, taken as 0.2; and f_{ii} is the coefficient of ice friction against ice, taken as 0.5.

(2) Spencer formula

Spencer et al[22] created a simple numerical formula to predict resistance in brash ice conditions from the model tests of three R-class icebreakers. The Spencer formula expressed ice resistance for low and high-friction ships, respectively. Ice resistance calculated with high friction was almost twice that of low friction. Only the lower friction formula is discussed and compared in the following part. The formula for a low ice-hull friction coefficient is as follows:

$$R_{ice} = 0.90F_h^{-0.739}\rho_i Bh_i V^2 + 1.31\Delta\rho gh_i BT \tag{19}$$

2 Formulas appropriate for ice resistance calculation of Arctic LNG carriers

The research objective of this study is an Arc7 ice-class LNG carrier with a capacity of 174 000 m^3 in four tanks insulated with an NO96 GW membrane containment system. The LNG carrier can break through level ice up to 1.5 m thick without the help of any icebreaker. The forebody configuration was designed to have an extreme ice bow with a downward ice-breaking pattern, and the main parameters of the ship are shown in Tab.2.

Tab.2 Principal dimensions of the full-scale ship

Parameter	Value
Length, L /m	295
Breadth, B /m	49.8
Design draught, T /m	12.0
Waterline angle, α/°	39
Stem angle, φ/°	32

2.1 Ice model test

A series of ice model tests for an Arctic LNG carrier were carried out in the ice basin of Krylov State Research Center (KSRC). A ship model with a scale of 1:33 was manufactured. A series of tests under different ice conditions, including level ice, broken ice, and brash ice, were carried out to obtain the ice resistance of the ship in different ice conditions. The test program of the experiment is shown in Tab.3. The ship model was attached to the towing dynamometer with operating propellers during the tests. The force was measured under the specified model movement speed according to the procedure recommended by ITTC[23-24], as shown in Fig.1.

Tab.3 Ice model test program matrix

Ice type	Test No.	Test speed		Ice thickness	
		Model /($m\cdot s^{-1}$)	Full-scale /kn	Model /mm	Target full-scale /m
Level ice	101	0.18	2	50	1.5
	102	0.22	2.5	49	1.5
	103	0.27	3	47	1.5
	104	0.36	4	48	1.5
Broken ice	201	0.27	3	45	1.5
	202	0.36	4	45	1.5
	203	0.45	5	45	1.5
	204	0.54	6	45	1.5
Brash ice	301	0.27	3	120	4
	302	0.36	4	120	4
	303	0.45	5	120	4
	304	0.54	6	120	4

(a) Level ice condition

(b) Broken ice condition

(c) Brash ice condition

Fig.1 Ice test scenario of the Arctic LNG carrier in KSRC

2.2 Comparison results

Ice resistance of the Arctic LNG carrier under different ice conditions is calculated according to the above semi-formulas, and the result is compared with the ice model test results. The appropriate formulas are selected by comparing the outcome between semi-empirical formulas and the ice model test.

(1) Level ice condition

Ice resistance in level ice conditions is calculated using semi-empirical formulas and compared with model test results. The values are calculated at different speeds, given the ice thickness is 1.5 m.

According to the comparison results, the Jeong formula underestimates the ice resistance by 40.1% on average. The reason is that the formula is obtained based on the low friction of 0.02, while the friction measured in the model test is 0.08, and the difference in friction between different ships is not included in the formula. In contrast, the Lindqvist formula estimates ice resistance well with the experimental results(Fig.2), and the average error between the formula and experimental results is 0.9%. So Lindqvist formula is relatively appropriate for the level ice resistance calculation of the Arctic LNG carrier.

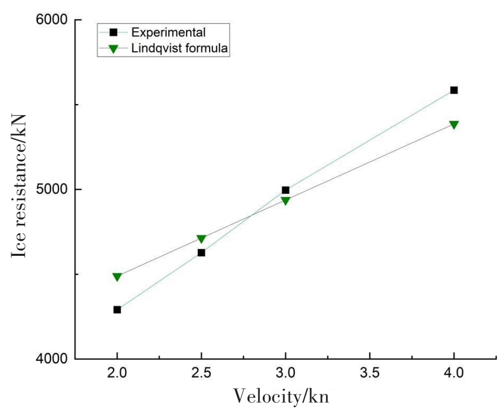

Fig.2 Comparison of ice resistance in level ice condition

(2) Broken ice condition

Ice resistance in broken ice conditions is calculated using semi-empirical formulas and compared with model test results. The values are calculated at different speeds, given the ice thickness is 1.5 m.

The resistance estimated by Zuve & Dobrodeev formula is close to the experimental results, and the average error in all cases is 8.5%(Fig.3). The resistance calculated by the original Zuve formula is smaller than that by Zuve & Dobrodeev formula, and the average error of the original Zuve formula is 19.4%. By comparing the error between Zuve & Dobrodeev formula and the original Zuev formula, it can be concluded that Zuve & Dobrodeev formula improves the prediction accuracy of broken ice resistance in the channel. Woolgara & Coulbourne formula predicts the lowest ice resistance among the three formulas by underestimating the ice resistance by 24.2%. Woolgara & Coulbourne formula's error is predictable because the channel width effect is neglected. So, the Zuve & Dobrodeev formula is relatively appropriate for the broken ice resistance calculation of the Arctic LNG carriers.

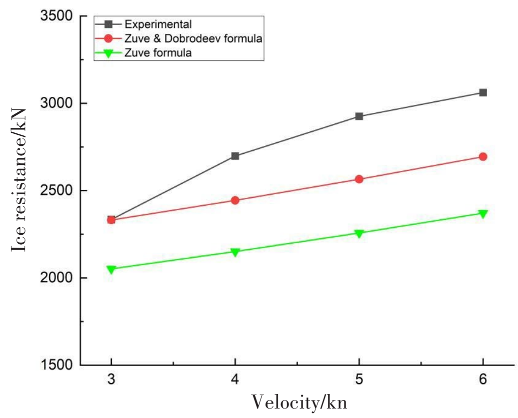

Fig.3 Comparison of ice resistance in broken ice condition

(3) Brash ice condition

Ice resistance in brash conditions is calculated using the semi-empirical formulas above and compared with model test results. The values are calculated at different speeds, given the ice thickness is 4 m.

According to the results, ice resistance calculated by the Dobrodeev formula coincides with the experimental results, and the average error is 3.1% (Fig. 4). In contrast, the Spencer formula gives a more significant prediction result, which overestimates the resistance up to 11.5% on average. So, the Dobrodeev formula is relatively appropriate for the brash ice resistance calculation of the Arctic LNG carriers.

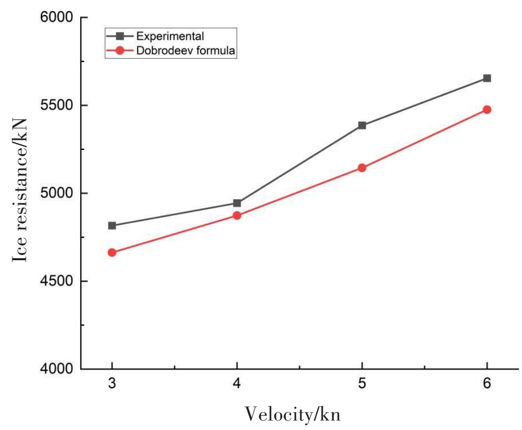

Fig. 4 Comparison of ice resistance in brash ice condition

3 Analysis of the influence of critical parameters on ice resistance

3.1 Key parameters affecting ice resistance

According to the comparison results in Section 2.2, the Lindqvist formula is appropriate for ice resistance calculation in level ice conditions, Zuev and Dobrodeev formula is suitable for ice resistance calculation in broken ice conditions, the Dobrodeev formula is proper for ice resistance calculation in brash ice conditions.

As for ship designers, it is meaningful to find the key parameters governing the ice resistance of ice-going vessels and investigate the influence of these parameters. Thus, these parameters will be considered in the preliminary design of a hull form. To identify the critical parameters of a ship hull or ice characteristics affecting ice resistance in different ice conditions, parameters used in the above-selected semi-empirical formulas are listed in Tab.4.

Tab.4 Summary of parameters considered in the selected semi-empirical formulas

			Level ice	Broken ice	Brash ice
Ship related parameters	Ship length/ L	m	L	–	L
	Ship breadth/ B	m	B	B	B
	Ship draft/ T	m	T	–	T
	Parallel mid-body length/ L_{par}	m	–	–	L_{par}
	Waterline angle/ α	°	α	α	α
	Stem angle/ φ	°	φ	φ	φ
Ice related parameters	Speed/ V	m/s	V	V	V
	Ice thickness/ h_i	m	h_i	h_i	h_i
	Channel width/ B_c	m	–	B_c	–
	Ice flexural strength/ σ_f	Pa	σ_f	–	–
	Ice Elastic modulus/ E	Pa	E	–	–
	Ice Poisson's ration/ ν	–	ν	–	–
	Ice density/ ρ_i	kg/m^3	ρ_i	ρ_i	ρ_i
	Water density/ ρ_w	kg/m^3	ρ_w	–	ρ_w
	Brash ice porosity/ n	–	–	–	n
	Ice concentration/ s			s	
	Hull-ice friction/ f	–	f	–	f
	Ice-ice friction/ f_{ii}	–	–	–	f_{ii}
	Cross-section area of ice pile by ship's side/ S_{PM}	m^2	–	–	S_{PM}

As shown in Tab.4, a total of 20 different parameters are included in these formulas. These parameters are divided into two categories: 6 ship-related parameters and 14 ice-related variables. Some parameters have a high frequency of occurrence, such as ship speed and breadth. In contrast, some have low frequency, e.g., ice concentration. The three formulas have different considerations of ice resistance components and include various parameters. 13 parameters are included in the Lindqvist formula, 5 of which are ship-related parameters and 8 of which are ice-related parameters. Only 8 parameters are included in Zuev & Dobrodeev formula, 3 are ship-related parameters, and 5 are ice-related parameters. 14 parameters are included in the Dobrodeev formula, 6 of which are ship-related parameters, and 8 are ice-related parameters. The number of ice-related differences is obvious among the three formulas because of the difference in ice properties under different conditions. But the number of ship-related parameters varies non-obviously among the three formulas, especially crucial parameters such as ship breadth, waterline angle, and stem angle are considered in all three formulas. These three parameters describe the characteristics of the bow shape of an Arctic LNG carrier.

In the preliminary design stage, adjusting the ship-related parameters to obtain lower ice resistance is convenient. Research on the influence of ship-related parameters can provide a clue to reducing ice resistance for ship designers in the initial stage. Thus, the sensitive analysis of the impact of three ship-related parameters appearing in all the three formulas will be discussed in detail: ship breadth, waterline angle, and stem angle. The three parameters affect the shape of the ship's bow.

3.2 Sensitive analysis of the bow shape parameters

In order to deeply reveal the relationship of each ice parameter (ship breadth, waterline angle, stem angle, etc.) with ice resistance and provide a guide for the preliminary hull form design, a sensitivity analysis on the parameter is carried out, and the influence on ice resistance of the three parameters is discussed.

Based on the initial case, we change the value of one parameter at a time. Meanwhile, other parameters remain the same. The parameters of the initial case and the corresponding changing intervals are listed in Tab.5. Then, the resistance of the LNG carrier under three typical ice cases with modified parameters is calculated according to the semi-empirical formulas. In the three specific cases covering different ice conditions of level ice, broken ice, and brash ice, the thickness of ice is the same as in the experimental tests. Since ice resistance almost has a linear relation with speed, a specific rate is set in each calculation case. The three ice cases are as follows:

1) Case A: Level ice condition, the thickness of level ice is 1.5 m, the carrier is ahead running at a speed of 2.5 kn;

2) Case B: Broken ice condition, the thickness of broken ice is 1.5 m, the carrier is ahead running at a speed of 3 kn;

3) Case C: Brash ice condition, the thickness of brash ice is 4 m, and the carrier is ahead running at a speed of 5 kn.

Tab.5 Variation of parameters

Parameter	Initial	Lower limit		Upper limit		Interval	
		Value	Percent	Value	Percent	Value	Percent
Ship breadth/ B	49.8	39.84		59.76		2.49	
Waterline angle/ α	39	31.2	+20%	46.8	−20%	1.95	5%
Stem angle/ φ	32	25.6		38.4		1.6	

(1) Influence of ship breadth

The change in ice resistance versus the variation in ship breadth is shown in Fig.5. Ice resistance increases with the increment of ship breadth in all three ice conditions. Furthermore, variation of the ice resistance has a linear fitting relationship with the ship breadth in all the three ice conditions. The influence of the ship breadth is the most significant in broken ice conditions, and ice resistance increases by 41% as ship breadth increases by 20%; ice resistance decreases by 34% as ship breadth decreases by 20%. The influence of ship breadth in brash ice conditions is similar to that in the broken ice condition. Ice resistance increases by 39% as breadth rises by 20% and decreases by 39% as breadth decreases by 20%. The influence of ship breadth in level ice condition is the smallest among the three conditions; ice resistance increases by 17.3% as breadth increases by 20% and decreases by 17.4% as breadth decreases by 20%.

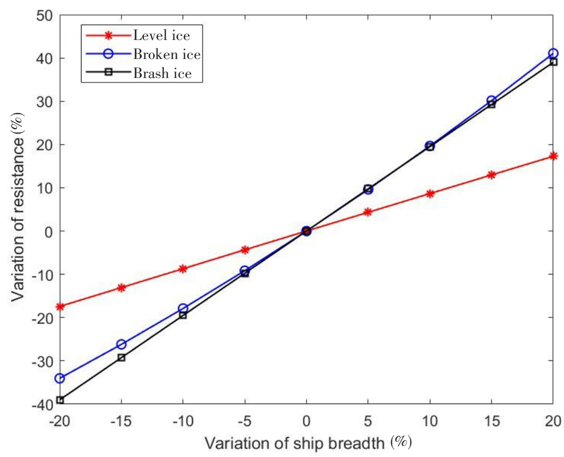

Fig.5 Change of ice resistance versus variation of ship breadth

In general, ship breadth significantly influences ice resistance under all ice conditions. As for the ship design, lowering the ship breadth is beneficial for reducing ice resistance. But as one of the ship's main dimensions, ship breadth is usually determined according to the ship's cargo capacity, so ship breadth is the first key parameter to be determined in the design.

(2) Influence of waterline angle

The change in ice resistance versus the variation in ship breadth is shown in Fig.6. Ice resistance decreases with the increment of waterline angle in all the three ice conditions, and the variation of ice resistance has a 2nd-order linear relationship with the variation of waterline angle. The influence of the waterline angle is the most significant in the brash ice condition. Ice resistance decreases by 21.7% as the waterline angle increases by 20% and increases by 31.7% as the waterline angle decreases by 20%. The influence of the waterline angle in level ice conditions is less than that in brash ice conditions. Ice resistance decreases by 7.7% as the waterline angle increases by 20%, and increases by 17.9% as the waterline angle decreases by 20%. The influence of waterline angle in broken ice conditions is the smallest of the three ice conditions. Ice resistance decreases by 3.2% as the waterline angle increases by 20%, and increases by 6.0% as the waterline angle decreases by 20%.

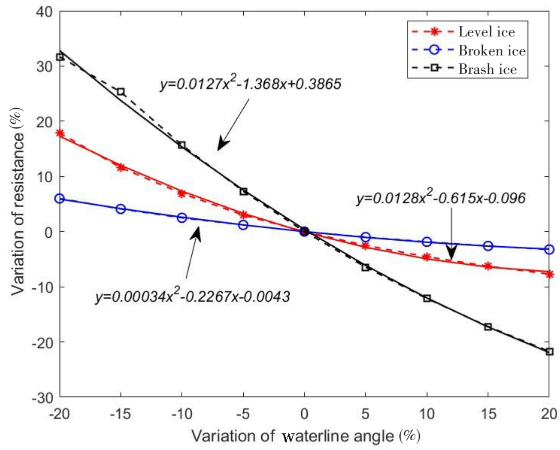

Fig.6 Change of ice resistance versus variation of waterline angle

As for the ship design, increasing the waterline angle is beneficial for decreasing the ice resistance. Further, increasing the waterline angle can effectively reduce ice resistance in brash ice and level ice.

(3) Influence of stem angle

The change of ice resistance versus the variation of stem angle is shown in Fig.7. Ice resistance increases with the increment of stem angle in level ice and broken ice conditions; variation of ice resistance has a 2nd-order linear relationship with the interpretation of stem angle. Especially in level ice conditions, ice resistance increases by 17.3% as the stem angle rises 20%, and decreases by 11.7% as the stem angle falls 20%. Relatively, the influence of stem angle in broken ice conditions is less than that in level ice conditions. Ice resistance increases by 7.6% as the stem angle rises by 20%, and decreases by 5.2% as the stem angle falls by 20%. It seems that ice resistance in brash ice conditions

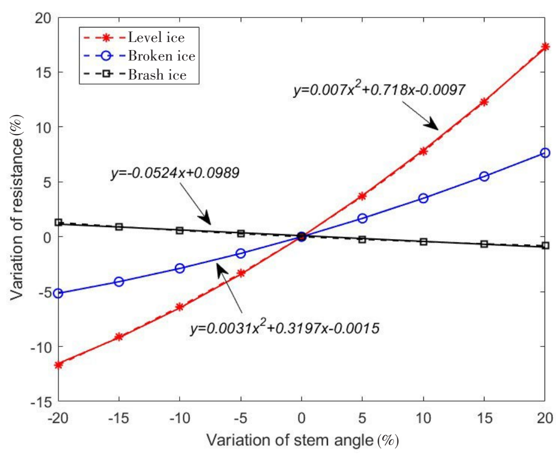

Fig.7 Change of ice resistance versus variation of stem angle

is not sensitive to stem angle; the variation of resistance is less than 1.5% as the variation of stem angle is within 20%. As for the ship design, reducing the stem angle is beneficial for decreasing the ice resistance in level and broken ice.

4 Discussion of bow shape optimization

According to the previous analysis result in Section 3.2, a small ship breadth, a large waterline angle, and a small stem angle are beneficial for reducing ice resistance. As one of the ship's main dimensions, ship breadth is mainly determined by the vessel's cargo capacity requirement. Usually, it is difficult to adjust the ship breadth to obtain efficient ice resistance. When designing the bow structure's hull form, changing the waterline and the stem angle is more practical to reduce the ice resistance. Ice resistance for different combinations of the waterline angle and stem angle is calculated. The calculation result in level ice condition with a thickness of level ice of 1.5m at the speed of 2.5 kn is shown in Fig.8.

The figure is divided into two parts (Zone *A* and Zone *B*) by the curve of 4750 MN, which is the ice resistance of the original bow shape. In Zone *B*, ice resistance is larger than that in the original bow design; in Zone *A*, ice resistance is lower than that in the original bow design. In Zone *A*, several combinations of waterline angle and stem angle are chosen to reduce the ice resistance. The following three combinations are considered:

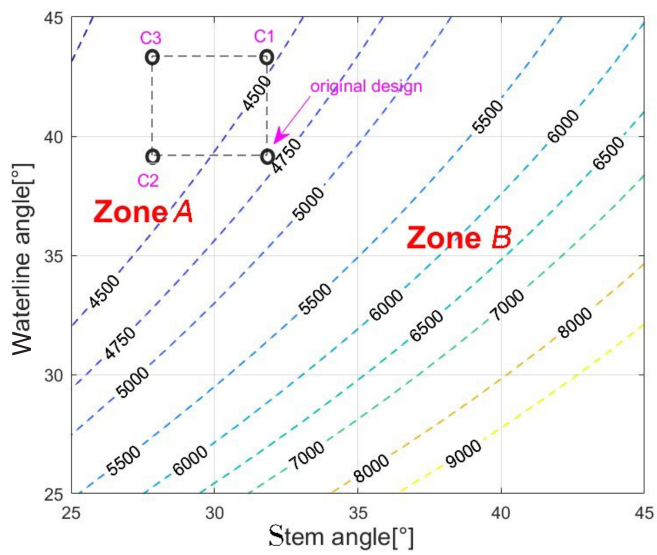

Fig.8 Level ice resistance of the carrier under different bow shapes

Combination 1: α=42.9°, φ=32°, the waterline angle was increased by 10%. In contrast, the stem angle was the same as the original design, as Point C1 shows in Fig.8.

Combination 2: α=39°, φ=28.8°, the stem angle was reduced by 10%. In contrast, the waterline angle was the same as the original design, as Point C2 shows in Fig.8.

Combination 3: α=42.9°, φ=28.8°, the waterline angle was increased by 10%, and the stem angle was decreased by 10% simultaneously, as Point C3 shown in Fig.8.

Ice resistance with the optimized combination of bow shape under different ice conditions is calculated by the formulas chosen in Section 2.2, and the calculation result is shown in Tab.6. In level ice conditions, Combination 1 reduces ice resistance by 4.6% on average, Combination 2 reduces ice resistance by 6.4% on average, and Combination 3 reduces ice resistance by 9.9% on average. Combination 3 can reduce ice resistance by 4.3% in broken ice conditions, and optimizing the bow shape has little influence on resistance in broken ice conditions. Combination 1 can reduce the ice resistance by 11.8% on average in brash ice conditions. Combination 3 can reduce ice resistance by 11.3% on average. The reduced margin of Combination 3 is a little less than that of Combination 1, and it is because that stem angle has a little negative effect of ice resistance in brash ice conditions. By comparing the ice resistance effect among three combinations under different ice conditions, Combination 3 with both a lower waterline angle and a larger stem angle is generally adequate for ice resistance reduction for multiple ice conditions.

Tab.6 Change of ice resistance with the optimized bow shape

Ice type	Ice thickness /m	Velocity /kn	Ice resistance vs Original design		
			Combination 1 α=42.9°, φ=32°	Combination 2 α=39°, φ=28.8°	Combination 3 α=42.9°, φ=28.8°
Level ice	1.5	2	−4.5	−6.3	−9.7
		2.5	−4.6	−6.4	−9.8
		3	−4.6	−6.5	−10.0
		4	−4.8	−6.6	−10.3
Broken ice	1.5	3	−1.9	−2.9	−4.3
		4	−1.9	−2.9	−4.3
		5	−1.9	−2.9	−4.3
		6	−1.9	−2.9	−4.3
Brash ice	4	3	−12.1	0.6	−11.6
		4	−11.9	0.5	−11.5
		5	−11.7	0.5	−11.3
		6	−11.5	0.5	−11.0

5 Conclusions

This paper identifies proper semi-formulas for ice resistance of the Arctic LNG carriers, and the influence of bow shape on ice resistance for the Arctic LNG carriers is investigated based on semi-empirical methods. The main findings are as follows:

(1) Lindqvist formula is appropriate for ice resistance estimation of the Arctic LNG carriers in level ice condition, Zuev and Dobrodeev formula is suitable for ice resistance estimation of the Arctic LNG carriers in broken ice condition, and Dobrodeev formula is proper for ice resistance estimation of the Arctic LNG carriers in brash ice condition.

(2) Ice resistance increases with increased ship breadth in all three ice conditions. In comparison, ice resistance decreases with the increment of waterline angle in all three ice conditions. Ice resistance increases with the increment of stem angle in level and broken ice conditions, especially in level ice condition. Small ship breadth, large waterline angle, and small stem angle are beneficial for reducing ice resistance.

(3) Optimized bow shape with both a large waterline angle and a low stem angle is suggested. The optimized bow shape can decrease ice resistance by 9.9% in the level ice condition and reduce ice resistance by 11.3% in the brash ice condition.

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首部设计对破冰型LNG船冰阻力影响研究

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摘要:为理解船首形状对冰载荷的影响，同时为前期的船首线型设计提供指导，基于半经验公式法开展船首形状对破冰型LNG船冰阻力的影响研究。首先，总结不同冰况下适用于货船冰阻力估算的半经验公式。然后，根据半经验公式估算结果与冰池试验结果的对比，确定适用于不同冰况下LNG船冰阻力估算的半经验公式。对比结果表明，Lindqvist公式适用于层冰的冰阻力估算，Zuev-Dobrodeev公式适用于破冰航道的冰阻力估算，Dobrodeev公式适用于碎冰航道的冰阻力估算。接着，分析所选公式中关键参数对冰阻力的影响。船宽、水线角、首倾角等描述船首形状特征的参数对船舶的破冰性能影响较大。在所有冰况中，冰阻力均随船宽的增大而增大，冰阻力随水线角的增大而减小。在层冰和碎冰条件下，冰阻力均随首倾角的增大而增大。较小的船宽、较大的水线角和较小的首倾角有利于降低冰阻力。最后，通过增加水线角和减小首倾角对船首形状进行优化，优化船首后的LNG船在层冰工况下可降低9.9%的冰阻力，在碎冰工况下可降低11.3%的冰阻力。

关键词: 破冰型LNG船；冰阻力；层冰；碎冰；屑冰；半经验公式

中图分类号: U661.31 **文献标识码:** A

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