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Method on continuous ice-breaking capability assessment of icebreaker

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Abstract. The opening of the Ice Silk Road is a great significant for the realization of the close connection with the European, and it is a promotion for China's economic development. The icebreaker will play an important role in the Arctic strategy. More accurate ice load calculation and prediction of ice breaking capacity methods will provide important technical support for the design and construction of icebreaker. This paper aims to solve the above problems and carry out the following research work. The ice load in continuous icebreaking type is calculated in 3D numerical method. Then, the motion differential equation in time history is established to calculate the motion response. In addition, the structure strength under ice breaking condition is evaluated based on FEM. At last, the evaluation method of continuous ice breaking capacity is proposed in this paper. Compared with the results of literature, the accuracy of the ice load calculated by this method meets the requirements and could further guide the design and development of ice breaking vessels.

1. Introduction

Global warming has become the common consensus, with the Arctic ice melting, to build "Ice Silk Road" is a new point to promote the Eurasian Economic Union docking based on The Belt and Road Initiative. The icebreaker operate in high latitude and severe cold regions, and ice load becomes the key factor to restrict ship structure safety and ice breaking capacity.

Continuous ice breaking means that icebreaker moves forward with a steady speed, which is the main operation mode. The ice load and the structure strength are important concerns in this condition. The research in this field is relatively limited, many problems need to be solved. Considering the situation, the purpose of this paper is to establish a theoretical prediction method for ice load and ice breaking capability, and make a solid theoretical foundation for model tests in the future. The research results also provide technical support for independent research and development of icebreaker design in China.

2. Rules for icebreaking capacity

This section will focus on the ice breaking capacity evaluation method. In order to calculate the capacity, the following factors should be taken into account[1]:

a. The thrust of the propulsion system is sufficient to meet the ice breaking demand.

b. The structural safety of icebreaker is sufficient to satisfy the ice breaking condition.

The continuous ice breaking capacity is depend on the more accurate environment load calculation. Considering the mass distribution and thrust force, it is the key to solve icebreaker motion response which could show the curve between ice thickness and breaking velocity in maximum thrust force, and then, it is necessary to check the safety of the ship structure in each design ice conditions. Through the above steps, it is obtained that the envelope of the icebreaker continuous icebreaking capability curve. The figure.1 shows the flow-process diagram of the calculation.

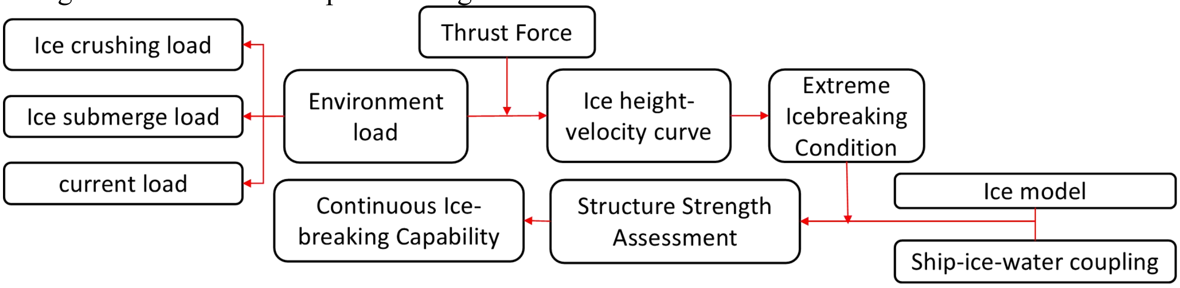

Figure 1. Flow-process diagram of the calculation.

3. Environment Load Calculation Method

The ice crushing load, ice submergence and current are the main loads of icebreaker during operation. Among these components, the ice crushing load is the control load of icebreaker in the process. The calculate method would be proposed in this part.

3.1. *Ice crushing load*

The action of ship ice is the process of contact-extrusion-bending failure[2]. Therefore, the ice breaking load is the integral of the action load of the sea ice which is squeezed by the contact with the hull.

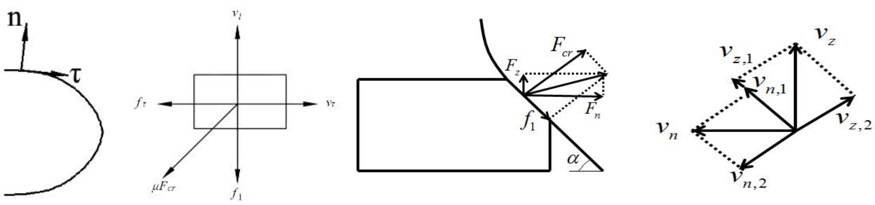

Figure 2. Schematic of the whole contact force system.

The coordinate system and section form of ship ice contact are shown in figure 2. The ice breaking load mainly contains two kinds of calculation components:

a. Extrusion caused by contact between sea ice and hull,

b. Friction caused by the relative motion between the hull and sea ice;

The crushing force F_{cr} is normal to the contact surface. And determined by the ice crushing strength σ and contact area A .

$$F_{cr} = \sigma A \tag{1}$$

On the contact surface, the relative velocity between ship and sea ice could be decomposed into the horizontal relative velocity component v_τ and v_1 , and the normal velocity component v_n . f_1 and f_τ are the frictional force in opposition to motion. So the force component could be expressed as:

$$f_1 = \mu F_{cr} \frac{v_1}{\sqrt{v_1^2 + v_\tau^2}} \tag{2}$$

$$f_\tau = \mu F_{cr} \frac{v_\tau}{\sqrt{v_1^2 + v_\tau^2}} \tag{3}$$

$$F_n = F_{cr} \sin\alpha + f_1 \cos\alpha \tag{4}$$

where μ is the frictional coefficient between ice and hull, α is the normal angle between ship and ice surface.

The ice crushing force of six degrees in the global coordinate system is as follows:

$$F_x = -F_n \cos\beta - f_\tau \sin\beta \tag{5}$$

$$F_y = F_n \sin\beta - f_\tau \cos\beta \tag{6}$$

$$F_z = F_{cr} \cos\alpha - f_1 \sin\alpha \tag{7}$$

The expression of ice breaking load in ship coordinate system is obtained by further deformation:

$$F_1^{brk} = F_x \cos\psi \cos\theta + F_y \sin\psi \cos\theta - F_z \sin\theta \tag{8}$$

$$F_2^{brk} = F_x\left(-\sin\psi\cos\varphi + \cos\psi\sin\theta\sin\varphi\right) + F_y\left(\cos\psi\cos\varphi + \sin\varphi\sin\theta\sin\psi\right) + F_z\cos\theta\sin\varphi \tag{9}$$

$$F_3^{brk} = F_x\left(\sin\psi\sin\varphi + \cos\psi\sin\theta\cos\varphi\right) + F_y\left(-\cos\psi\sin\varphi + \cos\varphi\sin\theta\sin\psi\right) + F_z\cos\theta\cos\varphi \tag{10}$$

$$F_4^{brk} = y_b F_3^{brk} - z_b F_2^{brk} \tag{11}$$

$$F_5^{brk} = y_b F_1^{brk} - x_b F_3^{brk} \tag{12}$$

$$F_6^{brk} = x_b F_2^{brk} - y_b F_1^{brk} \tag{13}$$

where (x_b, y_b, z_b) is the coordinate of ship ice contact point in the fixed ship coordinate system, and the above is the expressions of ice resistance caused by extrusion during ice breaking process in six degrees.

3.2. *Ice submerge load*
The resistance caused by ice floe clearing and submergence could be considered according to the formula proposed based on Lindqvist[3].

$$\begin{aligned} R_s = (\rho_w - \rho_{ice}) \cdot g \cdot h_i \cdot B\Big(T\left(T+B\right)/\left(B+2T\right) + \\ \mu_i\Big(0.7L - T/\tan\phi - B/4\tan\beta + T\cos\phi\cos\gamma\sqrt{1/\sin\phi^2 + 1/\tan\beta^2}\Big)\Big) \end{aligned} \tag{14}$$

where ρ_{ice} is the sea ice density, L is the ship length, B is the beam, T is the draft. ϕ is the slop angle of the ship hull, β is the waterline angle.

$$\gamma = \arctan\left(\frac{\tan\phi}{\sin\beta}\right) \tag{15}$$

3.3. *Current load*
The resistance of the current is also one of the load components concerned. As this component is not the focused force, this paper uses the calculation method in the literature [4] to calculate.

$$F_1^c(t) = \frac{0.075}{\left(\log_{10} R_n - 2\right)^2} \cdot \frac{1}{2}\rho_w S u\left|u\right| \tag{16}$$

$$F_2^c(t) = \frac{1}{2}\rho_w \int_L C_D(x) D(x) v(x)\left|v(x)\right| dx \tag{17}$$

$$F_6^c(t) = \frac{1}{2}\rho_w \int_L C_D(x) D(x) v(x)\left|v(x)\right| x dx \tag{18}$$

where S is the wet surface area, $C_D(x)$ is the drag coefficient and $D(x)$ is section draft.

4. Structure Assessment Method
The dynamic analysis method is used to evaluate the structural strength of icebreaker based on the finite element software. This part focuses on the coupled dynamic analysis method of ship-ice-water.

4.1. *Ice Model*
Sea ice is a nonlinear and extremely strong material [5]. In order to match the ice layer properties, the sea ice modeling criteria are summarized as follows by comparing the calculation results of various working conditions with the relevant technical literature:

a. Six body units is chosen to simulate the ice unit.

b. The size of sea ice unit could meet the requirements of engineering and precision.
c. Sea ice radiation region needs to meet the non-reflection condition.
d. Ice boundary conditions set for rigid fixation for large enough ice sheet.

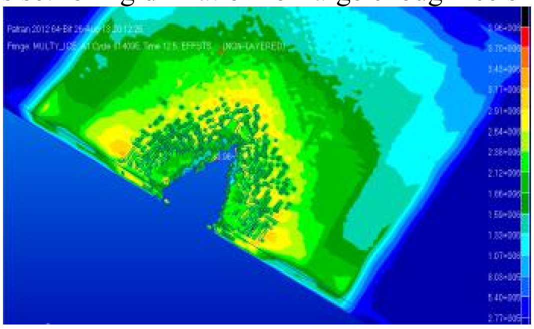

Figure 3. Nonlinear characteristics of sea ice.

Based on the previous research results of the authors, multiple failure criteria could be used to simulate the failure modes of sea ice. The damage pattern is shown in the figure.3.

4.2. *Second development of dynamic analysis*

The second development of dynamic analysis is mainly embodied in the following two aspects, and the program is compiled in the figure.4.

a. The new sea ice materials and failure criteria.
b. The coupling analysis model.

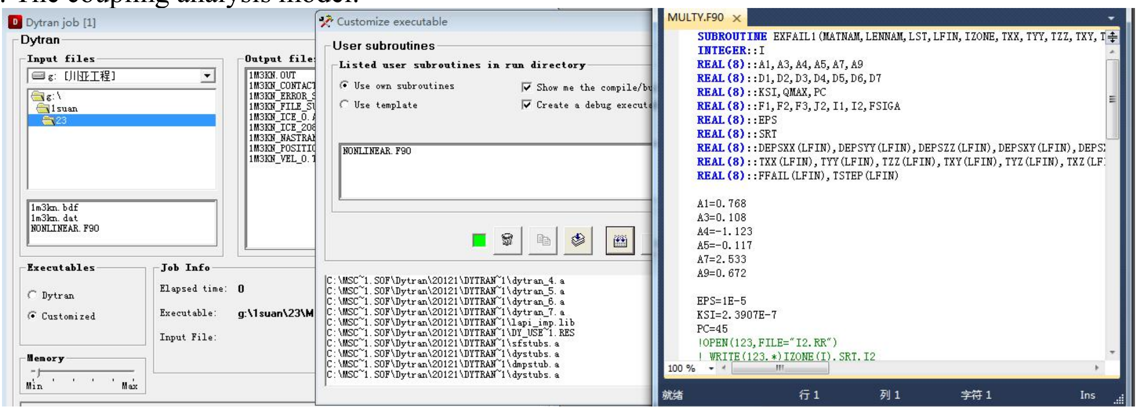

Figure 4. Second development of dynamic analysis.

5. Results and Discussion

According to the evaluation method of continuous ice breaking capacity proposed in this paper, a complete calculation of the ice breaking capacity of an icebreaker is carried out in this section, and the results are discussed in further. First, ice load is calculated in some ice thickness. And the motion response is solved through the motion differential equation. The preliminary h-v curve is contained according to the calculation results which meet the thrust requirements. Then the strength of hull structure under ice breaking condition is checked. Thus the ice breaking capacity of icebreaker is determined

5.1. The parameter of icebreaker and ice

The main parameter of the icebreaker and ice are shown in table1 and table 2.

Table 1. Main particulars of the icebreaker.

Length (m)	Beam (m)	Draft (m)	Displacement (t)	Mass inertia ($t \cdot m^4$)		
				I_{xx}	I_{yy}	I_{zz}
96.0	18.4	5.2	4890	1.39e8	2.44e9	2.57e9

Table 2. Main particulars of ice.

Density (kg/m^3)	Young Modulus (MPa)	Poisson ratio	Bending Strength (MPa)	Friction Coefficient
915	5400	0.33	0.75	0.15

5.2. Ice load calculation

In this part, the time domain ice load calculation program is used as a tool to predict the stable ice breaking speed under a fixed thrust force. When the speed is stable, it indicates that the ship could continue to break ice under this ice condition.

Figure.5 is the stable ice breaking speed and ice breaking load under the thickness of the 0.4m. The results shows that the mean ice force is about 2.15×10^5N, and the ice breaking velocity is 11kn. Compared with the Lindqvist [3] result, the accurate of this paper is satisfied. The ice load curve shown in figure.6 reflects its characters. When the ice contact occurs, the ice force increases gradually, and the ice force drops suddenly when the ice layer is destroyed. The fluctuating ice force at the bottom reflects the effect of ice floe on the structure. The variation of ice load presents periodicity. The thickness of ice layer under different ice thickness can be calculated in this method.

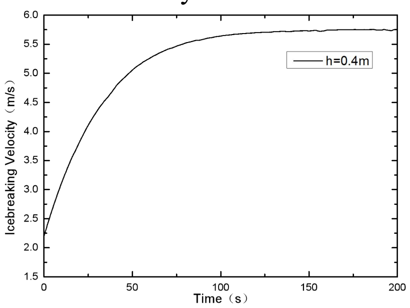

Figure 5. Velocity of icebreaking.

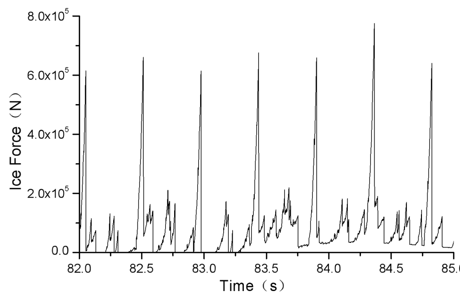

Figure 6. Ice Loads in numerical Method.

Table 3 gives the comparison of the ice load calculation results of the two ice thicknesses between this paper and the literature, and the accuracy is satisfactory.

Table 3. Results of breaking force in straight way.

Ice Thickness	0.4m	0.6m
Steady Velocity	11 kn	9 kn
Results in this paper	2.15×10^5N	4.02×10^5N
Results in Lindqvist[3]	2.53×10^5N	3.93×10^5N

5.3. Assessment of icebreaker structure

According to the calculation results of the previous section [6], the following cases are selected to check the structure strength. The load cases are listed in table 4.

Table 4. Load case of bow part in continuous-breaking way.

Case ID	Icebreaking Velocity	Ice Thickness
1	3.5kn	1.0m
2	8.9kn	0.6m
3	12.2kn	0.3m

The model is established according to the finite element model criterion. Coupling ship, ice and water, the dynamic analysis of the structure is carried out which is shown in figure.7. The analysis results are shown in the figure.8 and figure.9.

Under the ice breaking condition, the stress concentration area of the bow is concentrated in the transverse frame, the side plate and the transverse bulkhead area. As the ship ice breaking process needs not only to further resist the longitudinal ice breaking load, but also to withstand the side extrusion from the sea ice to the ship body mechanism.

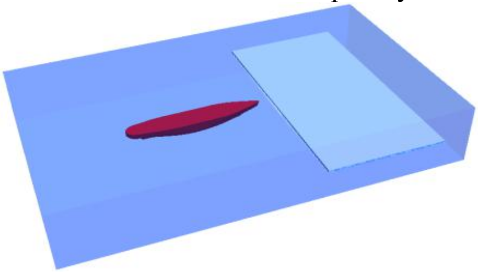

Figure 7. The couple model.

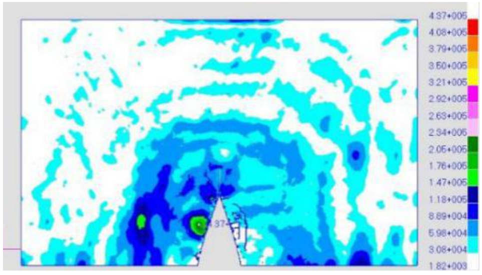

Figure 8. The stress distribution of ice.

The largest stress area appears in the transverse frame. For different ice thickness conditions and different ice breaking speed, it is found that the stress of the ship structure does not only increase with the ice thickness, but has a certain relationship with the ice breaking speed. The safety stress level is 330MP. So the ice breaking capacity curve is shown in figure.10.

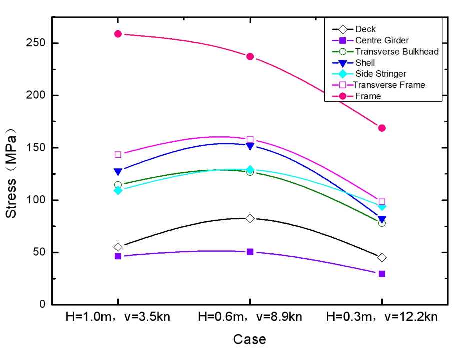

Figure 9. The structure stress summary.

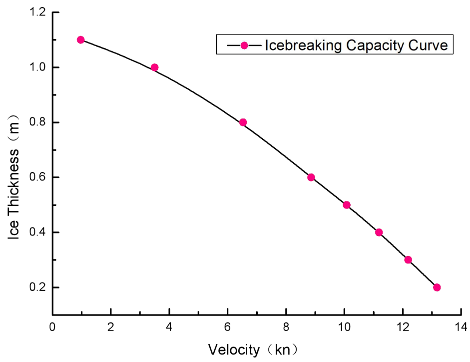

Figure10. Ice breaking capacity curve.

6. Conclusions

The calculation and analysis of ice load and the evaluation method of ice breaking capacity are the theoretical basis and core research contents. Through the study of this paper, the following conclusions are obtained:

The time domain calculation method of continuous ice breaking load and ship motion is developed. And the calculation accuracy is satisfied.

Put forward a set of evaluation method of ice ship icebreaking capability. And structure and load are considered.

Acknowledgments

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