A STUDY OF THE RESISTANCE PREDICTION METHOD IN LEVEL ICE

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ABSTRACT

A semi-empirical model to predict resistance in level ice is presented. Ice resistance is divided into the three components: crushing, bending, and submersion in this study. The relationship between the indentation energy and kinetic energy is also used to determine the contact area and force for the normal direction. In particular, the crushing and submersion components are calculated from Lindqvist's model, whereas the bending component is calculated from the newly presented formula. The calculated ice resistance results, which vary with ship speed and ice thickness, are compared with the results from other empirical analytical models. Then, the possible applications of the proposed model are discussed.

INTRODUCTION

When a ship navigates the arctic and sub-arctic regions, ice resistances occur. Therefore, the performance of the ship in ice can be affected by these forces. The prediction of icebreaking performance and resistance in level ice is a fundamental area of research, so many researchers have been focused on ship-ice interaction in order to understand the icebreaking phenomena, and analytical or empirical approaches were also introduced to determine the resistance of a ship in ice. For example, Lindqvist (1989) presented a relatively simple empirical formula. This model is a function of the main particulars of the ship, hull form, ice thickness, ice strength, and friction. The wedged bow shape is considered, and the ice resistance is divided into three parts, namely crushing, bending, and submersion, in Lindqvist's model. Riska *et al*. (1997) also studied ice resistance prediction. This model can be used for calculating resistance in level ice and the empirical coefficients in this model are derived from the full-scale data of a number of ships in the Baltic Sea. Meanwhile, the concept of energy consideration has been also introduced to estimate the ice force of a ship. Daley (1999) considered the relationship between the indentation energy and the kinetic energy and proposed various analytical formulas with which to calculate the ice collision forces. This method can predict the ice force for several geometric cases. Spencer and Jones (2001) investigated methods of predicting ice resistance, and they proposed the component-based ice resistance prediction method. This method is used in Canada's NRCC-IOT ice model basin to determine the ice resistance for various model-scale and full-scale icebreaking vessels. Recently, numerical analysis models have also been introduced to evaluate the manoeuvring performance and resistance of ships in ice (e.g. Liu *et al*., 2006; Su *et al*., 2010; Aksnes, 2011; Lubbad and Loset, 2011).
In this study, we present a semi-empirical model that can determine a ship's resistances in level ice based on Lindqvist's model. The presented model assumes that contact between the ship and the ice is a case of symmetrical collision, and two contact cases are considered. Then, the crushing and the submersion forces are calculated via Lindqvist's formulas, and the bending force is newly determined by the concept of energy consideration. Thereafter, the results from the presented model are compared with those of other empirical analytical models, namely Lindqvist's model and Riska's model, and the characteristics of ice resistance are discussed.

ICE RESISTANCE OF A VESSEL

Components of ship resistance in ice

To determine ship performance in ice, the propeller and rudder forces, hydrodynamic force, and ice force should be considered. The ice force is particularly significant in predicting the ice resistance. As mentioned in the introduction, ice resistance can be divided into crushing, bending, and submersion. In particular, Lindqvist's model assumes that the ice resistance, R_{ice}, increases linearly with the ship speed and the empirical constants in the velocity term are used for calculate the total ice resistance. In Lindqvist's model, ice resistance depends on the following variables:

$$R_{ice} = f\{ R_c , R_b , R_s \} \tag{1}$$

The failure mode of the ice floe is related to the ship-ice contact area. During the icebreaking process, if the contact area between ship and ice is quite small, the failure mode of the ice floe is composed of the crushing and shearing phases, but when the contact area is sufficiently large, bending failure occurs in the ice floe. After bending failure, broken ice pieces are submerged under the ship's bow and bottom. Thus, the submersion and friction force happens on the ship.

Ship and ice contact

To determine the projected contact area after impact, we assume that the ice floe is level ice and that ship-ice contact is a symmetrical (head-on) collision. This assumption implies that two ship-ice contact cases can be considered (see Figure 1).

Case I (Triangular crushing, $0 < \dfrac{\zeta_n}{\cos\varphi} \le h_i$*)*

$$A_n = \frac{\zeta_n^{\,2}}{\sin\varphi\cos\varphi}\frac{1}{\cos\beta} \tag{2}$$

Case II (Rectangular crushing, $\dfrac{\zeta_n}{\cos\varphi} > h_i$)

$$A_n = \frac{\zeta_n^{\,2}\cos\varphi(2-\cos^2\varphi)}{\sin\varphi}\frac{1}{\cos\beta} \tag{3}$$

In Equations (2) and (3), ζ_n and h_i denote the normal crushing displacement and ice thickness, respectively. Where φ and β are depicted in Figure 2.

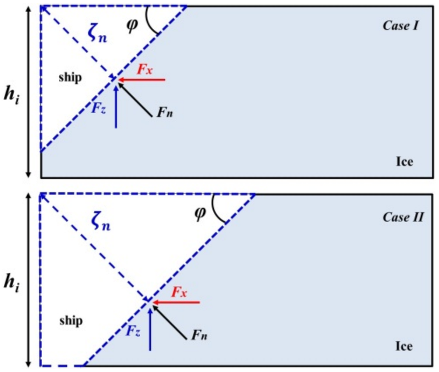

Figure 1. Contact area calculation.

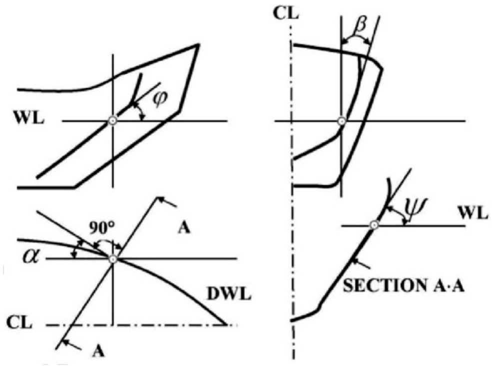

Figure 2. The definition of angle for ship geometry (Riska, 2010).

Breaking resistance

The breaking resistance is composed of the crushing and bending components. In this model a new formulation is proposed for the calculation of the bending component based on energy consideration. Firstly, the contact force according to the ship-ice interaction occurs in the normal direction. This force, F_n, can be calculated as

$$F_n = r\sigma_c A_n \tag{4}$$

Here, r is a contact coefficient that refers to the irregularity of the full-scale contact area (Lubbad and Loset, 2011), and σ_c is the compressive strength of the ice. In this model, r is 0.5, and this value is similar to the value proposed by Valanto (2001). For *Cases I* and *II*, the contact forces are assumed to be as follows:

$$F_n = r\sigma_c \frac{\zeta_n^{\ 2}}{\sin\varphi\cos\varphi}\frac{1}{\cos\beta} \qquad \textit{(Case I)} \tag{5}$$

$$F_n = r\sigma_c \frac{\zeta_n^{\ 2}\cos\varphi(2-\cos^2\varphi)}{\sin\varphi}\frac{1}{\cos\beta} \qquad \textit{(Case II)} \tag{6}$$

Then, the normal contact force can be divided into two components, namely the vertical component, F_z, and the horizontal component, F_x (Croasdale, 1980). In the presented model, these force components are related to the failure criterion of the ice floe and the ice resistance, respectively. Here, μ is the frictional coefficient.

$$F_z = F_n(\cos\varphi - \mu\sin\varphi) \tag{7}$$

$$F_x = F_n(\sin\varphi + \mu\cos\varphi) \tag{8}$$

In this model, the ice floe is assumed to be a semi-infinite beam on an elastic foundation. The bending failure of the ice floe is related to the maximum concentrated load per unit width, P_{max}, on the free edge of this semi-infinite beam. Therefore, the maximum concentrated load can be expressed by (Hetenyi, 1946):

$$P_{\max} = \sigma_f \frac{1}{1.469}\sqrt[4]{\frac{\rho_w g h_i^5}{E}} \tag{9}$$

Here, σ_f is the flexural strength of ice. E, ρ_w, and g denote the elastic modulus, seawater density, and gravitational acceleration, respectively. To determine the contact force, we first assumed that ship motion had only a small role in the process of icebreaking, and then, we calculated the maximum crushing displacement based on the relationship between indentation energy and kinetic energy. The indentation energy was the integral of the normal contact force on the normal crushing displacement. Here, M_e and V_n denote the equivalent mass of the ship and the normal velocity at the impact point, respectively. A detailed explanation can be found in Daley (1999).

$$IE_{ice} = KE_{ship} \rightarrow \int_N F_n d\zeta_N = \frac{1}{2}M_e V_n^{\ 2} \tag{10}$$

In the ice resistance calculation, the failure criterion should be determined in order to define the failure mode of the ice floe. If the maximum concentrated load, P_{max}, is larger than the vertical force component, F_z, the failure mode of the ice floe is dominantly composed of the crushing and shearing phases, but when the vertical force component, F_z, sufficiently exceeds a maximum concentrated load, P_{max}, bending failure occurs. Based on these assumptions, the icebreaking force can be determined. In addition, the breaking resistance is assumed to be proportional to ship speed divided by square root of ice thickness times the gravitational constant and this assumption is similar to Lindqvist's model.

CALCULATED ICE RESISTANCE RESULTS

Two contact cases are considered in this model. The general icebreaking phenomena are similar to *Case I* because of the ice thickness and the strength of the ice. When the ice thickness is thin and the ice strength is weak or the ship speed is fast, *Case II* sometimes occurs during the process of icebreaking, but ship-ice contact is mainly of the sort represented in *Case I* when ice thickness and the strength of the ice are thick and strong, respectively. The characteristics of ice resistance for the variations in ice thickness are depicted in Figure 3, along with other empirical analytical models, and the sea ice properties used and main particulars of the KV Svalbard are summarized in Table 1.

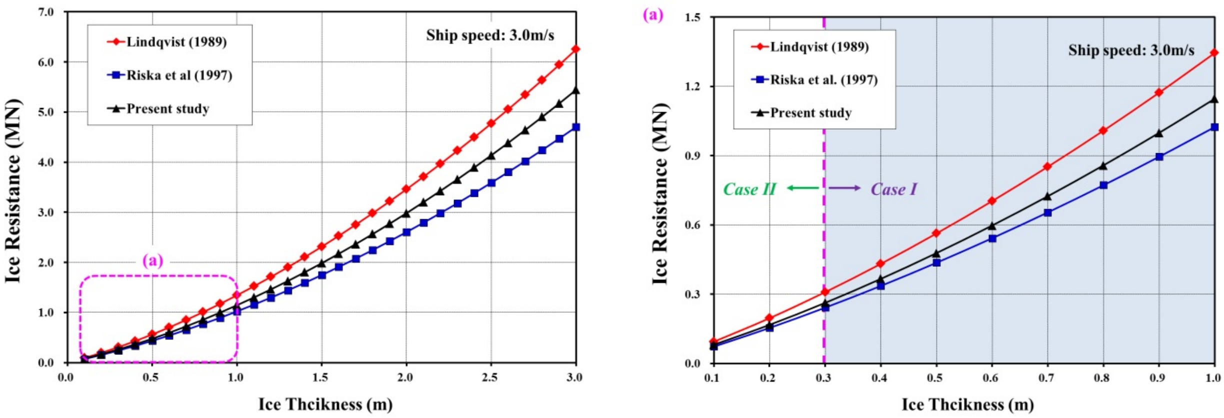

Figure 3. The relationship between ice resistance and ice thickness in comparison with those of other empirical analytical models

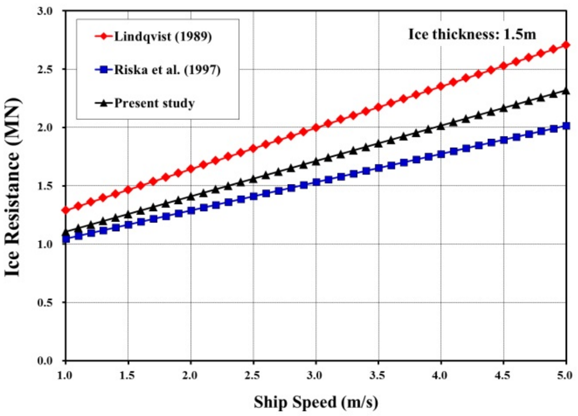

Figure 4. Comparison of ice resistance for ship speed with other empirical analytical models.

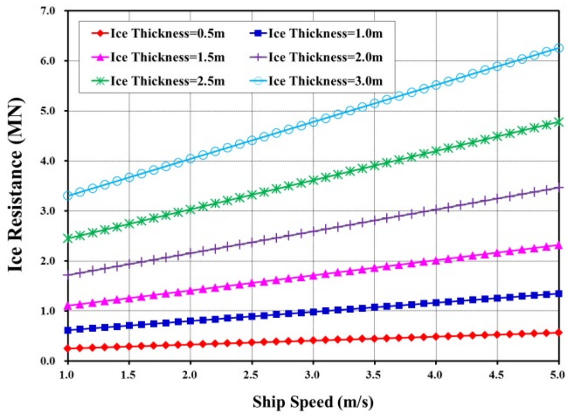

Figure 5. Calculated ice resistance for ship speed and ice thickness for the KV Svalbard.

Here, the presented model is located between Lindqvist's model and Riska's model. For example, at 1.0m in thickness and 3.0m/s of ship speed, the calculated resistances are 1.35MN, 1.02MN, and 1.15MN for Lindqvist's model, Riska's model, and the presented model, respectively. If the average ice thickness is roughly 1.5m during the arctic summer, the calculated ice resistances from the three empirical analytical models are depicted in Figure 4.

Here, the ice resistances increase linearly with ship speed. The calculated resistances are about 2.71MN, 2.02MN, and 2.32MN at 5.0m/s (about 9.72knots) of ship speed. In particular, the results of presented model have about 85.8% and 115.1% load levels for Lindqvist's model and Riska's model, respectively. Moreover, ice resistances derived from the presented model for various ship speeds and ice thicknesses are shown in Figure 5. In Figure 6 the ice resistances are calculated for three icebreaking vessels: the Terry Fox, KV Svalbard, and Araon. For the calculation of resistance, β is assumed to be 40°. In Figure 6, the calculated results for the KV Svalbard are quite similar to those of the Araon due to the similar main dimensions, and the Terry Fox has the lowest ice resistance. This reason for this is that the stem angle of the Terry Fox (23.3°) is smaller than that of other two icebreaking vessels (i.e., the KV Svalbard and the Araon are 34.0°). Although φ, α, ψ, and β are significant parameters in resistance calculation in level ice, small stem angle yields good icebreaking performance, therefore the resistances for the variation of stem angle are calculated, and these results are depicted in Figure 7. In this case, when the stem angle decreases by 42.9%, the ice resistance decreases by 19.4% at 1.0 m/s (about 1.94 knots) of ship speed and decreases by 20.4% at 5.0m/s of ship speed. Therefore, the ice resistance is slightly more reduced in high speed than low speed.

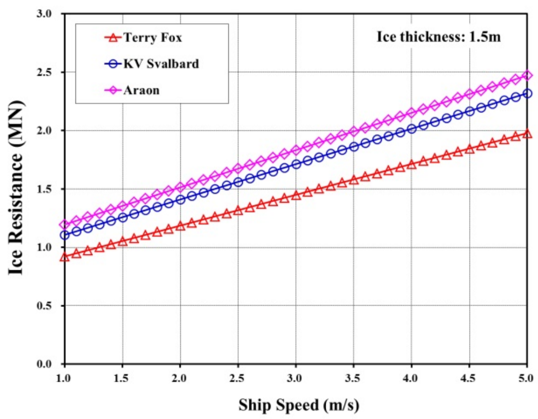

Figure 6. Comparison of calculated resistance results for three icebreaking vessels with respect to ship speed.

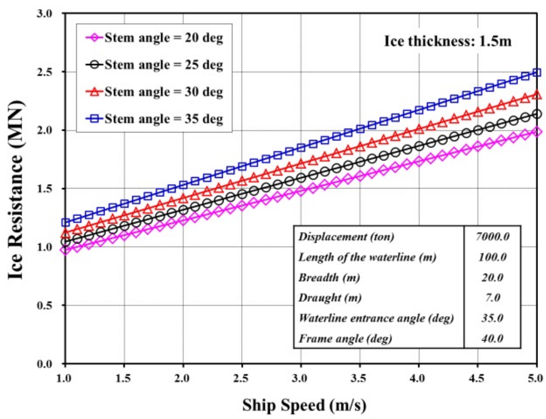

Figure. 7 The characteristic of ice resistance for various stem angles.

Table 1. The value used for the ice resistance calculation

Parameters	Value	Parameters of the KV Svalbard	Value
Elastic modulus (GPa)	5.40	Displacement (ton)	6375.0
Compressive strength of ice (MPa)	2.30	Length of the waterline (m)	89.0
Flexural strength of ice (MPa)	0.55	Length of parallel sides (m)	36.32
Poisson's ratio	0.33	Length of bow section (m)	27.24
Frictional coefficient	0.15	Breadth (m)	19.1
Gravitational acceleration (m/s^2)	9.81	Draught (m)	6.5
Seawater density (kg/m^3)	1024.0	Stem angle (deg)	34.0
Ice density (kg/m^3)	880.0	Waterline entrance angle (deg)	35.0

CONCLUSION

A semi-empirical method for resistance prediction in level ice based on energy consideration is introduced, and the simplified model is presented. Full-scale icebreaking phenomena are very complicated processes. Accordingly, practical contact cases are considered in this model.

In the calculations, *Case I* occurs more frequently than *Case II* due to the ice thickness and the strength of ice. Nevertheless, *Case II* sometimes occurs when the ice thickness is thin or the ship speed is fast on weak ice. The used energy approach for ship and ice contact in the breaking force calculation yields favourable results. However, the validation of this model is not straightforward due to the insufficiency of the full-scale data. Therefore, the estimated ice resistances are compared with those of other empirical analytical models. This model shows a moderate correlation with other empirical analytical models. Thus, the predicted resistance results indicate that it has reasonable load levels.

AKNOWLEDGEMENTS
This research was sponsored by the KIOST, MOERI (Project No. PES142C and PES156D) and by the Ministry of Knowledge and Economy, Korea (Project No. PNS184B).

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