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NSR TRANSIT SIMULATIONS BY THE VESSEL PERFORMANCE SIMULATOR "VESTA" PART 2 SIMPLE RESISTANCE FORMULAE OF SHIPS IN FLOE ICE

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ABSTRACT

Ships encounter various ice conditions such as level ice, ridged ice, floe ice and ice-clogged channel. Various models have been developed so far for the prediction of ice resistance in various ice conditions. The authors proposed the hybrid model of resistance prediction of ships navigating in floe ice including small ice floes, ice-clogged channel and a large ice floe.

This model consists of two existing models, i.e. Kashitelijan-Poznjok-Ryblin and Lindqvist model. The former model gives the ice load at the limit momentum condition and can be fundamentally applied to the resistance prediction of ships in small ice floes. The latter model is originally developed for resistance prediction in level ice. It gives the ice load at the limit stress condition and can be applied to the prediction in a large ice floe. Resistance in floe ice can be determined as the smaller resistance predicted by either of two models. The former model is also applicable to the resistance prediction in ice-clogged channel by taking the influence of the restricted ice area into account.

The accuracy of each model was validated through comparisons with the model-scale experiments conducted at the ice model basin of the National Maritime Research Institute. Validation study was also conducted through comparisons with the full-scale thrust measurements in the southern part of the Sea of Okhotsk, Japan. It is found that the proposed model is capable of predicting the resistance in floe ice of various sizes and concentrations with reasonable accuracy. This model is applicable to the transit simulation along the Northern Sea Route.

NOMENCLATURE

A:	Area of ice floes
B:	Ship breadth
B_c:	Channel width
C:	Concentration of ice (0: ice free, 1.0: fully ice-covered)
C_T:	Resistance coefficient of ships in ice-free water
C_{WE}:	Waterline coefficient at the forward part of the ship
d_i:	Floe size

E : Young's modulus of ice
F_L : Froude number based on ship length
F_h : Froude number based on ice thickness
h_i : Thickness of ice (including snow depth in case of full scale measurement)
L : Ship waterline length
L_H : Length from stem to parallel part of the mid-body
l_c : Characteristic length of ice
n_c : Channel width to ship breadth ratio
R: Resistance
S : Wetted surface area of ship
T : Ship draft
T_P : Propeller thrust
$1-t$: Thrust deduction factor
v : Ship advance speed
α : Waterline entrance angle
ϕ : Stem angle
φ : Angle between the normal of the surface and a vertical vector
μ : Friction coefficient between hull and ice
ν : Poisson ratio of ice
ρ : Density
σ_b : Flexural strength of ice

Suffix
i: Ice
LF: Large Floe
LM: Limit Momentum
LS: Limit Stress
o: Values at the stem
SF: Small floe
w: Water

INTRODUCTION

Recently the retreat of summer Arctic sea ice is noticeable and the number of ships navigating along the Northern Sea Route (NSR) has increased significantly. In order to enhance a sustainable development of NSR, it is crucial to predict ship performance accurately and to evaluate the economical and environmental impacts by shipping along NSR. We are developing the ice navigation simulator "VESTA in ice" for the transit simulation along NSR (Matsuzawa et al., to be published in 2015).

A lot of researches have been conducted of the ice navigation simulations along NSR (Patey and Riska, 1999, Reimer and Duong, 2013, Erceg et al., 2013, Valkonen and Riska, 2014). Most researches focused on the navigability of merchant ships with icebreaking capability. Considering the opportunities will increase for a large, ice-strengthened merchant vessel with insufficient icebreaking capability navigating in a mild ice condition, it is necessary to develop the resistance prediction formulae in floe ice including an ice-clogged channel.

Patey and Riska (1999) applied the model by Lindqvist (1989) for level ice to the resistance prediction in floe ice. In this model, ice breaking is one of the most dominant resistance components and thus regarded as a kind of the limit stress model (ISO19906, 2010). However in case that the floe size and concentration is relatively small, the lateral displacement of floes is dominant and a limit momentum model is required. One of such models was developed by Kashitelijan-Poznjok-Ryblin (Nozawa, 2006). Hereafter denoted as KPR model.

In the present study, we propose simple and hybrid formulae of resistance in floe ice with various sizes, concentrations with area restriction, using Lindqvist and KPR models. Validity of proposed formulae is confirmed by comparing with the results of the ice tank tests and the field measurements in the Sea of Okhotsk.

RESISTANCE FORMULAE IN FLOE ICE

Resistance Model in a Large Floe

In case a floe size is large enough compared to the ship dimensions, a floe is regarded as level ice. We adopt the model developed by Lindqvist (1989) as the resistance model in a large floe. This model considers the ice resistance as the sum of the components from ice failure by crushing (R_{LF1}) and bending (R_{LF2}), and submergence (R_{LF3}) of broken ice pieces. This model is regarded as a kind of the limit stress load model, in which local failure of ice governs the load (for example, ISO19906, 2010).

$$R_{LF} = R_{LF1} + R_{LF2} + R_{LF3} + R_W \tag{1}$$

$$R_{LF1} = R_c(1+1.4F_h) \tag{2}$$

$$R_{LF2} = R_b(1+1.4F_h) \tag{3}$$

$$R_{LF3} = R_S(1+9.4F_L) \tag{4}$$

Here

$$R_c = F_v \frac{\tan\phi_o + \mu\cos\phi_o / \cos\varphi_o}{1-\mu\sin\phi_o / \cos\varphi_o} \tag{5}$$

$$R_b = \frac{27}{64}\sigma_b B \frac{h_i^3}{l_c^2}\left\{\tan\phi + \frac{\mu\cos\phi}{\sin\alpha\cos\varphi}\right\}(1+\frac{1}{\cos\varphi}) \tag{6}$$

$$R_s = (\rho_w - \rho_i) g h_i B (T \frac{B+T}{B+2T} + \mu(0.7L - \frac{T}{\tan\phi} - \frac{B}{4\tan\alpha} + T\cos\phi\cos\varphi\sqrt{\frac{1}{\sin^2\phi} + \frac{1}{\tan^2\alpha}})) \tag{7}$$

$$R_W = \frac{1}{2}\rho_w v^2 S C_T \tag{8}$$

$$F_v = \frac{1}{2}\sigma_b h_i^2 \tag{9}$$

$$l_c = \left\{\frac{E h_i^3}{12\rho_w g(1-\nu^2)}\right\}^{0.25} \tag{10}$$

$$\varphi = a\tan(\tan\phi / \sin\alpha) \tag{11}$$

Resistance Model in Small Floes

In case a floe size is small compared to the ship dimensions and concentration is small, the lateral displacement of floes is dominant. We adopted the model by Kashitelijan, Poznjok and Ryblin (Nozawa, 2006) as the resistance model in small floes. This model assumes ice resistance in small floes as the sum of impact (R_{SF1}), dissipative (R_{SF2}) and static components (R_{SF3}). No failure and submergence of ice floes are taken into account in this model. Thus this model is regarded as a kind of the limit momentum load model, in which mass and velocity of ice floes governs the load.

$$R_{SF} = R_{SF1} + R_{SF2} + R_{SF3} + R_W \tag{12}$$

$$R_{SF1} = \bar{k}_3 \rho_i g d_i h_i L F_L^2 \tan^2\alpha \tag{13}$$

$$R_{SF2} = \bar{k}_2 \rho_i g d_i h_i B F_L (\mu + C_{WE}\tan\alpha) \tag{14}$$

$$R_{SF3} = \bar{k}_1 \rho_i g \sqrt{d_i h_i} (\frac{B}{2})^2 (1 + 4\mu C_{WE}\frac{L_H}{B}) \tag{15}$$

Here, $\bar{k}_1$, $\bar{k}_2$ and $\bar{k}_3$ are empirical constants. $\bar{k}_1$ and $\bar{k}_2$ are the function of ice concentration.

Resistance Model in Ice-clogged Channel

In KPR model, the resistance in ice-clogged channel is calculated by taking the influence of channel width to ship breadth ratio (Fig.1) into account for the expression of $\bar{k}_1$.

$$\bar{k}_1(C, n_c) = \left\{\frac{(C-0.5)\sqrt{\bar{k}_1(8, n_c)}}{3}\right\}^2 = \left\{\frac{(C-0.5)\sqrt{a_0 + a_1 n_c + a_2 n_c^2}}{3}\right\}^2 \tag{16}$$

$$n_c = B_c / B, \quad a_0 = 19.2282 \; a_1 = -3.1313 \; a_2 = 0.1474$$

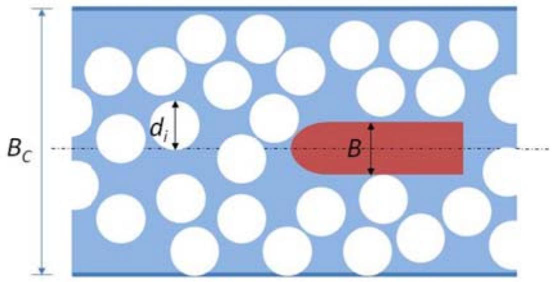

Fig.1. Schematic of Vessel Navigating in Ice-clogged Channel

Table 1. Parameters of KPR Model (n_c=10)

C	0.4	0.6	0.8	1.0
$\bar{k}_1$	0	0	0.027	0.074
$\bar{k}_2$	0.93	2.54	5.70	8.20
$\bar{k}_3$	4.30	4.30	4.30	4.30

VALIDATION OF RESISTANCE FORMULAE

Model-scale Experiment at Ice Model Basin

Model-scale experiment of icebreaker Soya was conducted at the ice model basin of the National Maritime Research Institute. Table 2 shows the principal dimensions of “Soya” in full and model scales.

(1) Wide channel

In this experiment, an ice sheet is cut into a lot of square shapes to simulate the ice condition of small ice floes (Fig.2). The side length of ice floe is 0.5 and 1.0m (10 and 20m in full scale), and ice concentration changes from 0 to 0.8. The ice thickness is typically 0.03m (0.6m in full scale). The density of model ice is assumed to be 0.940. The detail of the experiment is reported in Wako et al. (2000). The width of the ice model basin is 6m which corresponds to the channel width (B_c). Thus channel width to ship breadth ratio (n_c) is 6.0/0.78=7.69. Fig.3 shows the comparison between measured and predicted resistance by KPR model.

Table 2 Dimensions of Icebreaker Soya and its Scaled Model

Item		Unit	Full [m]	Model [m]
Length	L	m	90.2	4.5
Breadth	B	m	15.6	0.78
Draft	T	m	5.26	0.263

Fig.2 Ice-clogged Wide Channel

It is found that the prediction by KPR model is totally on safe side. Better agreement is observed in cases of smaller floes, lower ice concentration and lower ship speed. Fig.4 shows the ratio of the number of broken ice floes to the number of ice floes which contact with the model ship. The ratio is low in cases of smaller floes, lower ice concentration and lower ship speed. Icebreaking occurs if the force required to displace ice would exceed that to break ice. Thus it is reasonable to conclude that one of the reasons of this over-prediction is the effect of icebreaking which is not taken into account in KPR model. This is one of the motivations for developing the hybrid model of ice resistance formulae in floe ice.

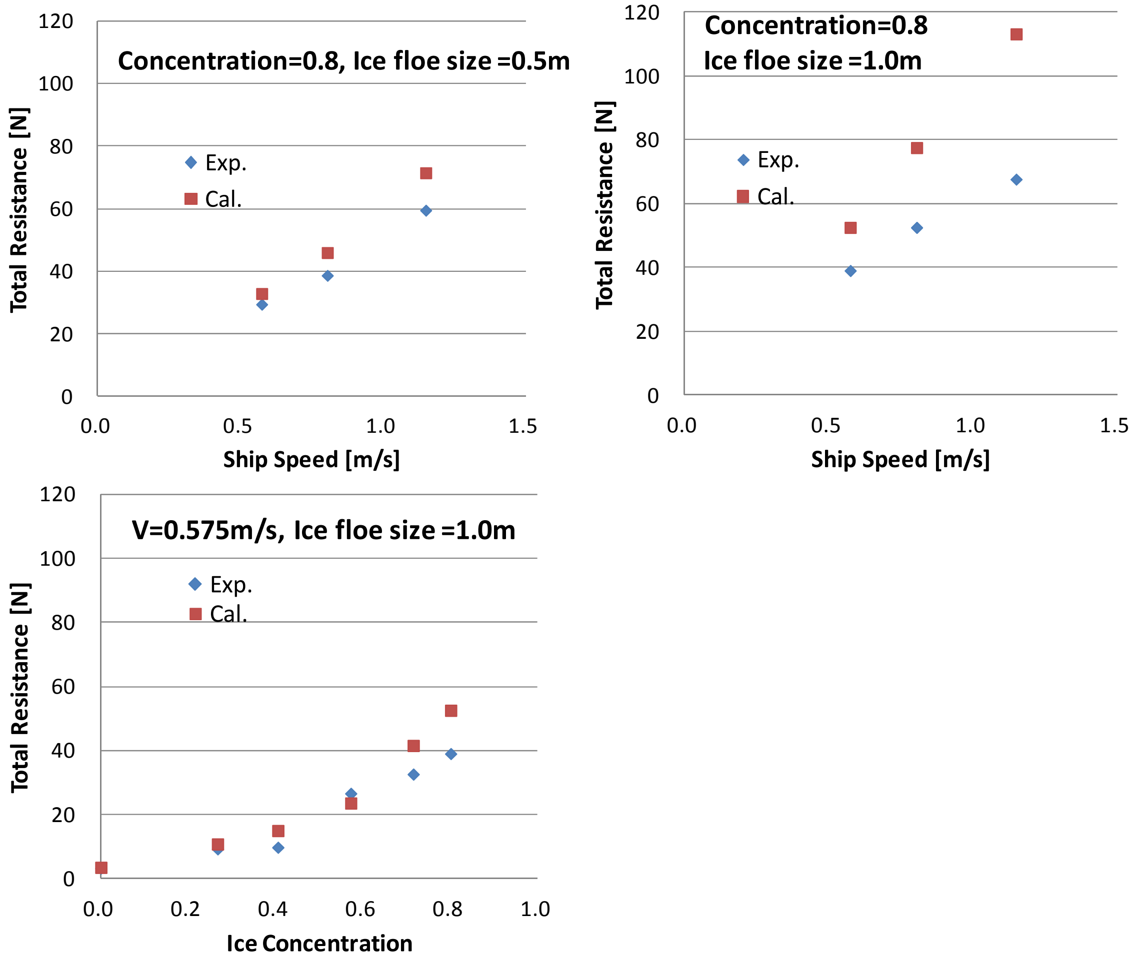

Fig.3 Comparison of Resistance in Ice-clogged Wide Channel
Exp. vs. Simulation (h=0.03m, n_c=7.69)

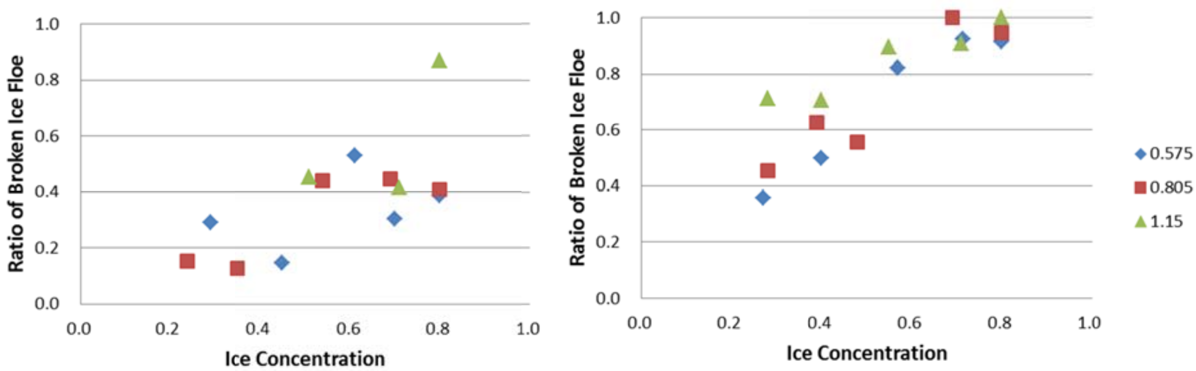

Fig.4 Relation of Broken -floe Ratio to Ship Speed and Ice Concentration
Size of Ice floe is Left：0.5m, Right：1.0m

(2) Narrow channel

In this experiment, the resistance test in narrow ice-clogged channel is conducted after the resistance test in level ice by the same model ship (Fig.5).

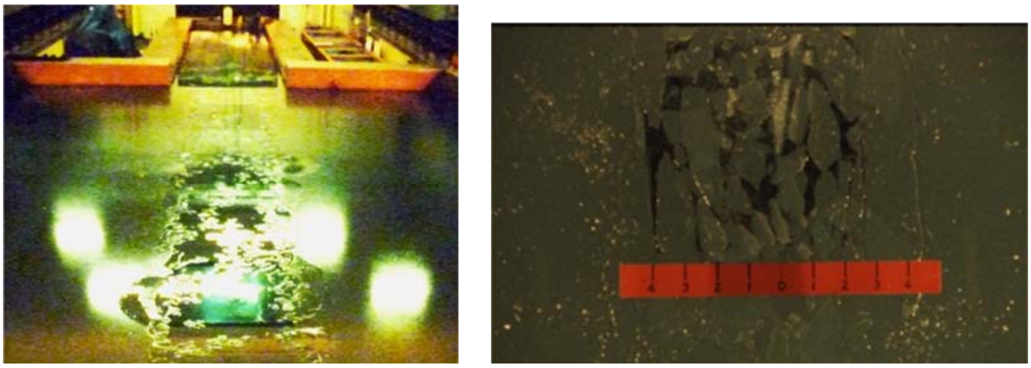

Fig.5 Ice-clogged Narrow Channel

Table 3 shows the conditions of channel. Concentration of ice is obtained by the image processing of photos as shown in the right of Fig.5. The width of the channel is calculated as the sum of ship breadth and 2 x ice thickness. The average area of ice floes is calculated by equation (17) (Tatinclaux, 1986).

Table3 Condition of Ice-clogged Narrow Channel

Case	h_i [m]		C	n_c
	Model	*Ship*		
1	0.0285	0.570	0.84	1.073
2	0.0148	0.296	0.69	1.038
3	0.0074	0.148	0.40	1.019

$$\frac{A}{h_i^2} = 0.105\frac{\sigma_b h_i}{\rho_w g} \tag{17}$$

Here flexural strength of model ice is assumed to be 30kPa.

Fig.6 shows the comparison between measured and predicted total and ice resistance by KPR model. The towing speed is 0.345m/s. The ice resistance is obtained by subtracting water resistance (R_W) from total resistance. The predicted ice resistance shows reasonable agreement in cases of thinner ice and lower ice concentration. The same trend is observed in case of wide channel.

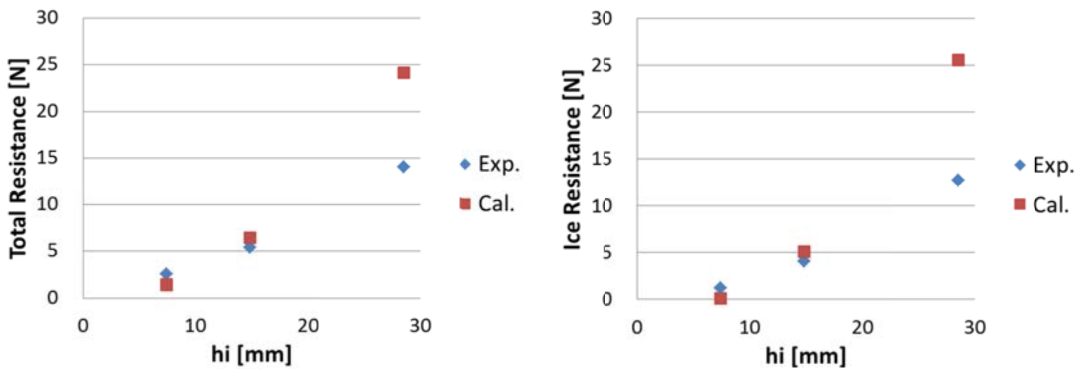

Fig.6 Comparison of Resistance in Ice-clogged Narrow Channel, Exp. vs, Simulation
Left : total resistance, right : ice resistance

Full-scale Experiment in the Sea of Okhotsk

National Maritime Research Institute has conducted the collaborative research with Japan Coast Guard since 1991. In 1997, we carried out the field measurements of propeller thrust of Icebreaker Soya in the South Okhotsk Sea. The detail of the measurements and results was reported in Uto et al. (1999). Table 2 shows the principal dimensions of Soya. Strain gauges were attached to the portside shaft and propeller thrust was derived from compressive strains. Ice thickness and concentration of ice are obtained by visual observations. Snow depth on ice is included in the value of ice thickness. Flexural strength of ice is calculated by the temperature and salinity of ice. Ship speed was measured by GPS.

Table 4 shows the summary of the thrust and ice properties measurements. Thrust is calculated by twice the measured average thrust because measurements were carried out at one of the two propeller shafts

Floe size is larger than 500m in case of large floes. For small floes, floe size is derived from the photographs around Soya and determined as 10m for each case.

Comparison of Resistance in Large Floe

Figs.7 and 8 show the comparison between measured and calculated resistance in a large floe. Resistance is obtained from equation (18) and measured thrust listed in Table 4.

$$R_{LF} = (1-t)T_P \qquad (18)$$

Here 1-*t* is thrust deduction factor and 0.9 from the experiments using the scaled model of “Soya”. Friction coefficient between hull and ice (μ) is set as a tuning parameter and determined to be 0.08. This value is somewhat lower than expected. In this calculation, we define ice thickness as ice thickness including snow depth. It gives higher ice breaking and submergence resistance. This might lead to lower friction coefficient. Reasonable agreement is obtained between measured and predicted resistance in a large floe.

Table 4. Results of Field Measurements

Test No.	Ice Thickness [m]	Ship Speed [m/s]	Thrust [kN]	Floe size* /Concent-ration
2401	0.31	2.5	392	L /1.0
2404	0.45	1.2	395	L /1.0
2407	0.35	1.0	133	L /1.0
2410	0.74	4.2	517	L /1.0
2501	0.34	3.3	233	L /1.0
2504	0.42	2.0	83	S/0.6-0.7
2505	0.48	5.5	370	S/0.6-0.7
2509	0.44	2.9	291	L /1.0
2512	0.39	6.9	424	L /1.0
2606	0.66	4.5	522	S/0.8-0.9
2607	0.94	1.9	761	L /1.0
2609	0.92	2.3	771	L /1.0
2701	0.45	3.7	220	S/0.9-1.0
2703	0.65	2.9	772	L /1.0

* L: Large floe size >500m, S: small

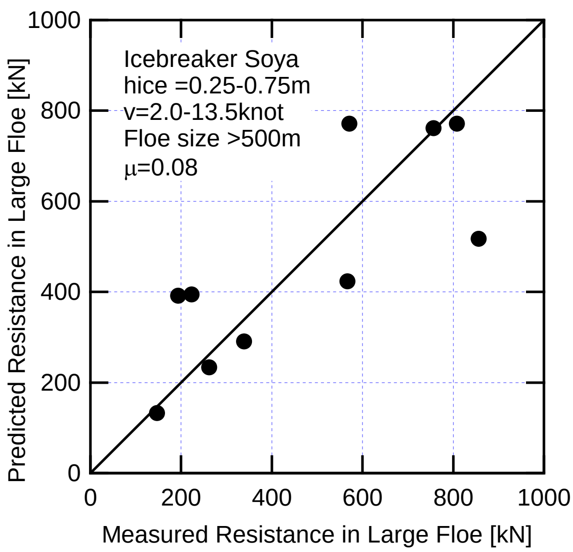

Fig.7. Comparison of Resistance in a Large Floe between Measured and Predicted

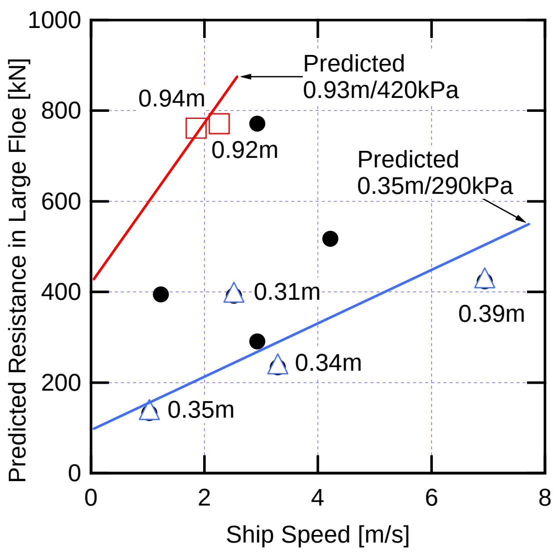

Fig.8. Comparison of Resistance versus Ship Speed in a Large Floe

Comparison of Resistance in Small Floes

Fig.9 shows the comparison between measured and calculated resistance in small floes. Ice concentration is given as the average value listed in Table 4, for example, 0.95 in Test No. 2701. The channel-width to ship breadth ratio n_c is large enough and the parameters listed in

Table 1 is used.

It is found that present model predict the resistance in small floes reasonably well. The model predicted the higher resistance at C=0.95. In this condition, ice failure and submersion would be more dominant than the cases with lower ice concentration. However these effects are not taken into account in the present model.

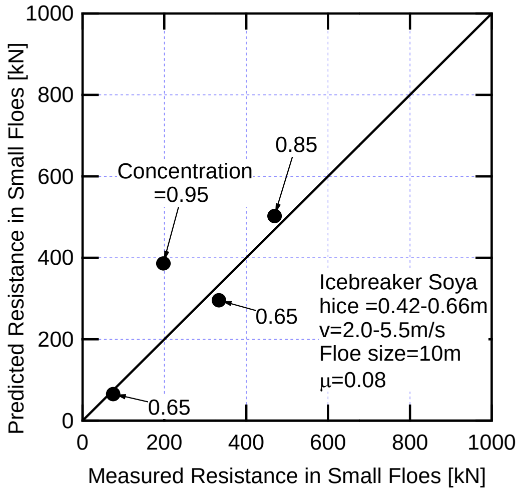

Fig.9 Comparison of Resistance in Small Floes between Measured and Predicted

Fig.10. Icebreaker Soya in small ice floes

HYBRID MODEL

The authors proposed the hybrid model of resistance which is applicable for floe ice with various size, concentration and areal restriction. The idea comes from the load scenario for the design of offshore structures in ice (ISO, 2010). Resistance of ships in floe ice is determined as the lower value from two load scenario, i.e., the limit momentum scenario where the load is determined by the mass and the relative speed of ice floe, and the limit stress scenario where the load is determined by the local ice failure.

The limit stress load model (LSM) in floe ice is obtained by extending the model by Lindqvist (1989). This model was used as the resistance model in floe ice in the NSR transit simulation (Patey. M. and Riska. K., 1999).

$$R_{LS} = C \times R_{LF} \tag{18}$$

The limit momentum load model (LMM) is KPR model.

$$R_{LM} = R_{SF} \tag{19}$$

The hybrid model of resistance in floe ice is obtained in eq.(20).

$$R_F = \min[R_{LS}, R_{LM}] \tag{20}$$

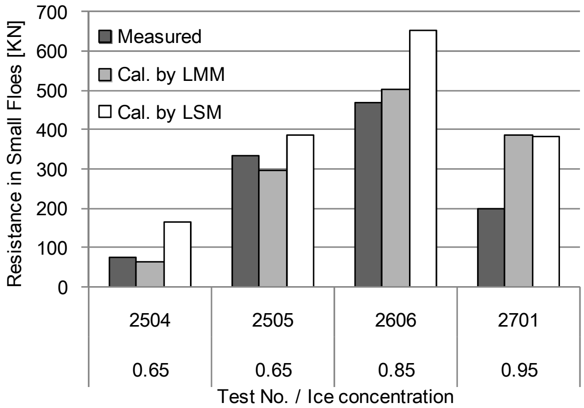

Fig.11 Comparison of Calculated Resistance in Small Floes between LMM and LSM

Fig.11 shows the comparison of the results of resistance in small floes calculated by the LMM and LSM. As the ice concentration higher, the difference becomes smaller. At the highest concentration of ice (Test No.2701), the resistance by LMM overestimates that by LSM and the resistance by the coupled model approaches to the measurement result.

CONCLUSIONS

The authors proposed the simple, hybrid formula of resistance which is applicable for floe ice with various size, concentration and areal restriction, by coupling the limit momentum and limit stress load models. The validity of each model is confirmed by comparing the results by resistance tests at the ice model basin and the field measurements in the south Okhotsk Sea. This model is applicable to the performance prediction of icebreakers and ice-going vessels in the initial design stage and to the transit simulation along the Northern Sea Route.

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