Journal of Ocean, Mechanical and Aerospace
-Science and Engineering-, Vol.45

July 30, 2017

Empirical Approach to Predict Ship Resistance in Level Ice

Jaswar Koto,[a,b,*] and Efi Afrizal,[b]

[a)]*Ocean and Aerospace Research Institute, Indonesia*
[b)]*Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Skudai, Johor, Malaysia*

*Corresponding author: jaswar.koto@gmail.com & jaswar@utm.my

Paper History

Received: 20-April-2017
Received in revised form: 25-June-2017
Accepted: 30-July-2017

ABSTRACT

Prediction of resistance of ship level ice is very important in initial stage of ship design due to related to propulsion and engine power of a ship. As model scale test is very expensive therefore an accurate tool is required to predict the resistance of a ship in ice. A semi empirical method to predict ship resistance in level ice based Koto method was presented. The ship resistance consisted of ice breaking force due to flexural strength of ice, submersion force due to buoyancy, friction force contact between ice and hull and loss momentum force due to collision. The simulation results were verified with experimental data of three icebreakers: MT Uikku, Hellay and Araon. The method was also compared with other empirical methods: Lindqvist, Riska, Keinonen and Jeong. It was founded that the average errors using the proposed method was 3 % for MT Uikku, 0.3 % for Hellay and 0.4 % for Araon.

KEY WORDS: *Ice Resistance; Ice Thickness; Icebreaker*.

NOMENCLATURE

AAT	Aker Artic Technology
DAT	Double Acting Tanker
DWT	Deadweight
MW	Mega Watt
NSR	Northern Sea Route

1.0 INTRODUCTION

The first model of ice basin was built in the Soviet Union by AARI, 1955. That was needed to observe either of hull form or propulsion could be effect to ice-breaking ship performance. In ice model test, Froude scaling law is using to associate ice model test and full scale situation. Wilkman (2015) revealed that total resistance is the summation of ice resistance and open water resistance [1 & 2]. Ice resistance is an amount of resistance to breaking ice, resistance of some component sink ice under hull and resistance velocity due to dynamic working. Experiment in ice model scale test can be contributed to reducing huge investment before the real ship was manufactured.

Design of ice-going ships requires considering the performance, adequate hull and strength of machinery and good functioning of the ship in ice condition and open water condition. Determining the ship resistance in the level ice is more complex than in the open water due to the changing characteristic properties of ice and icebreaking phenomena. Ship resistance at the ice level is very fundamental and crucial area and initial stage in ice ship designs, consequently many researchers have focused in ship-ice interaction.

The phenomenon of interaction between ice and ship has been carried out by researchers through empirical mathematical simulation such as Lewis.et.al (1970) [3] proposed a formula consists of ice breaking, friction, ice buoyancy and momentum. Crago et al. (1971) described a set of model test in "wax-type" ice on 11 icebreakers [4 & 5]. Enkvist (1972) studied three icebreakers: Moskva-class, Finncarrier, and Jelppari [4]. Milano (1973) made a significant advance in the purely theoretical prediction of ship performance on ice based on conservation energy [4]. Vance (1975) [4] obtained an "optimum regression equation" from five sets of model and full-scale data, of the Mackinaw same data as used by Lewis.et.al (1970). Lindqvist (1989) [6] developed a formula to calculate ice resistance based on many full scale tests in the Bay of Bothnia. Keinonen et al.

(1996) [7 & 8] did research on resistance of icebreaking vessels in level ice and developed a formula based on results of a study of escort operations involving five icebreaking vessels. Daley, Riska, et.al (1997 & 1998) [9] proposed a level ice resistance formula with some empirical parameters by developing Lindqvist's formula. J.Koto (2002 & 2005) proposed a method to predict ice resistance of double acting tanker running in unfrozen and frozen ice channels and level ice for dual-direction ship running ahead and astern [10 ~ 13] . Jeong et al. (2010) proposed new ice resistance prediction formula for standard icebreaker model using component method of ice resistance and also predicted the model test results to full-scale using calculated non-dimensional coefficients [14 & 15]. Tan et al. (2013 & 2014) studied the effect of the propeller-hull-ice interaction for running astern [16 ~ 19]. Hu.et.al (2015 & 2016) discussed on experimental and calculated ice resistances by some empirical formulas: Lindqvist, Keinonen, Riska and Jeong In level ice and channel ice [20 & 21]. They found the average error varied and very large as follows: 13% for Lindqvist, 50% for Riska, 7% for Jeong and 37% for Konenien [20 & 21]. Jeong.et.al (2017) presented a semi-empirical model to predict ship resistance in level ice based on Lindqvist model [15].

In the present study, the authors presented a method for calculating ship resistance in level ice. This method is expected to provide better accuracy than previous methods. The empirical method was developed based on Koto model. The ice-ship contact was derived into four forces which was ice breaking, submersion due to ice buoyancy, losing momentum due to collision and friction between ice and hull ship. The accuracy of ice resistance predicted by the Koto model was verified by test data of the icebreakers Healy, Araon and MT Uikku.

2.0 ICE RESISTANCE OF SHIP

Performance ship on ice was measurable in capability of ship to break ice and to manoeuvre in ice condition. That could be confirmed through achieved speed by ship when sailing in uniform or certain ice thickness, ice ridges or in the level ice condition (Wilcox, 1994). Figure.1 describes interaction happening between hull and ice including crushing, bending, submersion and friction of ice at bow hull. The velocity of ship on ice condition can be determined through thrust of propeller available to overcome the ice resistance. Performance of propulsion system can be improved through modification on hull shape and some change into propulsion design, both of that could minimize an effect of resisting forces and maximize the propulsive forces.

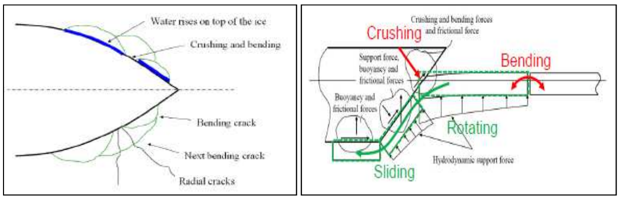

Figure.1: Hull and ice interaction (Wilcox, 1994).

The ice resistance is assuming linear to ship speed which composed of three components, like described in Equation (2.1):

$$R_{ice} = R_b + R_s + R_f \tag{2.1}$$

Each component R_b , R_s and R_f successively are breaking, submersion and friction components. The breaking component is related to break the ice such as crushing, bending and turning of ice. The submersion component is concerned to push the broken ice down along the ship hull. The friction component is connected to slide the broken ice along the ship hull. In general velocity of the ship depends on working ice resistance associated to friction component. The total resistance working on ice, R_{total} is the sum of ice resistance (R_{ice}) and open water resistance (R_{ow}) as expressed in Equation (2.2):

$$R_{total} = R_{ice} + R_{ow} \tag{2.2}$$

Jones (2004) has discussed in detail the history of icebreaking ship from what he considered the earliest true icebreaker, Eisbrecher-1 [4]. The icebreaker was operated between Hamburg and Cuxhafen, it was built in 1871 and in 1956 it was began to use bow propeller while penetrated on ice. Jansson also discussed the science of icebreaking. He quoted values for the physical properties of freshwater ice, at -3^0C

There was not mentioned of details experiments including that value, some addition information were only for coefficient of friction between ice and metal as 0.10 to 0.15 for fresh or Baltic ice and 0.20 for salt water or polar ice. He gave a simple formula for the total ice resistance as described in Equation (2.3):

$$R_{ice} = (C_1 . h + C_2 . h . v^2) . B \tag{2.3}$$

Where; C_1 and C_2 are experimental constants, h is ice thickness, v is vessel speed and B is breadth of vessel at waterline.

After that, Jones (2004) in his report said credited to Kashteljan et al. (1968) whom the first detailed attempt to analyse level ice resistance by breaking it down into components [4]. Where on the paper, it was appeared like an Equation (2.2) to determine the total of ice resistance, R_{TOT}:

$$R_{TOT} = k_1 \mu_o B \sigma h + k_2 \mu_o B \rho_i h^2 + k_3 \frac{1}{\eta_2} B^{k_4} v^{k_5} \tag{2.4}$$

Where; σ is ice strength, B is ship beam, h is ice thickness, v is ship speed, and ρ_i is the density of ice. μ_o and η_2 are related to Shimansky's ice cutting parameters, and k_1, k_2, k_3, k_4, k_5 are coefficients experimentally determined (0.004, 3.6, 0.25, 1.65, and 1.0 respectively).

In the Equation (2.4), that compose of several parts like, first component $R_1 = \mu_o B \sigma h$ is resistance due to breaking the ice, second component represented of $R_2 = k_2 \mu_o B \rho_i h^2$, is resistance due to forces connected with weight (such as submersion of broken ice, turning of broken ice, change of position of icebreaker, and dry friction resistance) and third is component of $R_3 = k_3 \frac{1}{\eta_2} B^{k_4} v^{k_5}$ for determined of resistance due to passage through broken ice

Lewis and Edwards (1970) gave a good review of previous work and derived the Equation (2.5) [3];

$$R_{im} = C_o \sigma h^2 + C_1 \rho_i g B h^2 + C_2 \rho_i B h v^2 \tag{2.5}$$

JOMAse | Received: 8-April-2017 | Accepted: 30-April-2017 | [(45) 1: 1-8]
Published by International Society of Ocean, Mechanical and Aerospace Scientists and Engineers, www.isomase.org., ISSN: 2354-7065 & e-ISSN: 2527-6085

Where; R_{im} is mean resistance excluding water, g is acceleration due to gravity and C_0, C_1, C_2 are non-dimensional coefficients to be determined experimentally.

The first term represents ice breaking and friction, the second accounts for all resistance forces attributable to ice buoyancy and the third accounts for all resistance forces attributable to momentum interchange between the ship and the broken ice.

They conducted non-dimensional analysis by dividing by σh^2 to obtain the Equation (2.6):

$$R' = C_0 + C_1 B' N_\Delta + C_2 B' N_I \quad (2.6)$$

Where; $R' = R_{im}/\sigma h^2$ is non-dimensional mean ice resistance, $B' = B/h$ is non-dimensional beam, $N_\Delta = \rho_i g h/\sigma$ is volume metric number and $N_I = \rho_i \sigma / v^2$ is inertial number

Crago et al. (1971) describe a set of model test in "wax-type" ice on 11 icebreakers [4 & 5]. By considering simple bow geometry and the vertical force acting on the ice sheet, they derived Equation (2.7) for the ice thickness (h);

$$\frac{h\sqrt{\tau}}{\sqrt{T_t}} = \frac{1.53}{\sqrt{\tan(i+\beta)}} \quad (2.7)$$

Where; τ is ice tensile strength, T_t is thrust, i is stem angle, $\beta = \tan^{-1} f$ and f is the coefficient of friction.

Enkvist (1972) made a major addition to the literature of ship performance in level ice [4]. On the article, he narrated experimental on model tests of three ships as follows: Moskva-class, Finncarrier, and Jelppari and were able to compare his results with limited full-scale data from all three icebreakers. From a combination of analytical work, dimensional analysis, and a few assumptions, they derived a semi–empirical Equation 2.8 where defined ice resistance based on three terms:

$$R_{ice} = C_1 B h \sigma + C_2 B h T \rho_\Delta g + C_3 B h \rho_i v^2 \quad (2.8)$$

Where; T is draft of ship, ρ_w is water density and ρ_i is ice density, $\rho_\Delta = \rho_w - \rho_i$

Milano (1973) made a significant advance in the purely theoretical prediction of ship performance on ice [4]. He considered the energy needed for a ship to move through level ice, which varied somewhat with ice thickness. For example, for very thick ice the ship moves through the ice-filled channel (E_1), impacts the various bow and cusp wedges causing local crushing (E_2), climbs onto the ice (E_3) until sufficient force is generated to cause fracture, at which time the ship falls (E_4), and moves forward, forcing the ice downward (E_5). The total energy loss due to ship motion can be calculated using Equation (2.9);

$$E_T = E_1 + E_2 + E_3 + E_4 + E_5 \quad (2.9)$$

Vance (1975) obtained an "optimum regression equation" from five sets of model and full-scale data, of the Mackinaw same data as used by Edwards et al. (1972), Moskza, Finncarrier, Staten Island, and Ermak. Equation (2.10) was resulted by regression to define ice resistance:

$$R_{(ice)} = C_S \rho_\Delta g B h^2 + C_B \sigma B h + C_V \rho_i V^2 L h^{0.65} B^{0.35} \quad (2.10)$$

Where; $R_{(ice)}$ is the resistance due to ice, L is length of vessel, and C_S, C_B, C_V are empirically determined values. The first term is a submergence term, the second a breaking term, and the third term is a velocity dependent resistance.

An example of a fit to his equation is shown in Figure.1 in which the Mackinaw full-scale data (label FS) are shown fitted to his equation above (label FSR) and a model-scale regression to his equation (MSR) is also shown. Good agreement is found between the model and full-scale results.

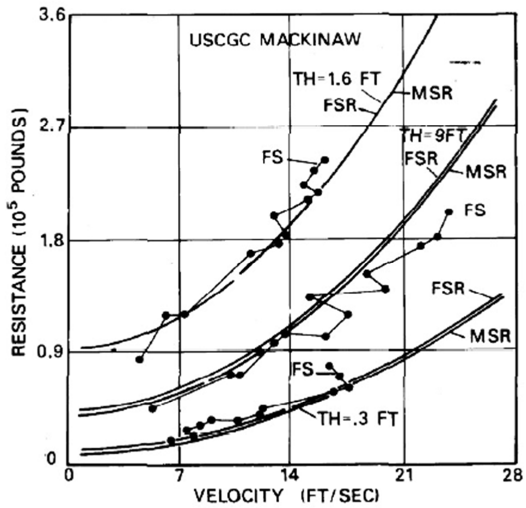

Figure 2: Result using optimum Regression (Vance, 1975)

Edwards et al. (1976) presented full-scale data for the Louis S. St. Laurent collected by analysing ramming type tests using Equation (2.11). The equation is in non-dimensional form.

$$\frac{R}{\rho_w g B h^2} = 4.24 + 0.05 \frac{\sigma}{\rho_w g h} + 8.9 \frac{V}{\sqrt{gh}} \quad (2.11)$$

Kotras et al. (1983) in his paper proposed an equation based on Nagle's thesis (Nagle, unpublished) which describe yet by another semi-empirical approach [4]. In his proposed equation the total ice resistance is given by

$$R_{ice} = R_B + R_{Bf} + R_T + R_{Tf} + R_S + R_{Sf} \quad (2.12)$$

Where; R_{ice} is total ship ice resistance, R_B, R_{Bf} are normal and frictional resistance due to breaking of level ice, R_T, R_{Tf} are normal and frictional resistance due to broken ice flows and R_S, R_{Sf} are normal and frictional resistance due to submerging broken ice

Since 1985, development of new icebreaking forms has been having significant value and more scientific approach had been used such as modelling of ships in ice with extensive model testing and, most recently, numerical methods. Canadian Arctic oil exploration and development led to new designs such as the Kigoriak, and Terry Fox, while other activities led to the Oden, double acting tankers (DAT) with Azipods, FPSO's in ice, and research ships such as the Nathaniel B. Palmer, USCGC Healy,

JOMAse | Received: 8-April-2017 | Accepted: 30-April-2017 | [(45) 1: 1-8]
Published by International Society of Ocean, Mechanical and Aerospace Scientists and Engineers, www.isomase.org., ISSN: 2354-7065 & e-ISSN: 2527-6085

and the converted CCGS Franklin now called CCGS Amundsen.

An interesting development in the middle 80's, Zhan et al. (1987) was made a full-scale resistance trial of the Mobile Bay in uniform level ice [4]. Denny (1951) had been reported the same term, in the principle the experiment method is parallels with the open water trials of the Greyhound (Froude, 1874) and Lucy Ashton. While such tests are clearly difficult to perform, in theory they provide a direct measurement of full-scale resistance. They also conducted full scale propulsion tests. They found the best fit to their towed resistance results was with the Equation (2.13):

$$\frac{R_{ice}}{\rho_w g B h^2} = C_0 + C_1 \frac{v^2}{gB} \cdot \frac{L^3}{h} \tag{2.13}$$

Where; $C_0 = 4.25$ and $C_1 = 3.96x10^{-5}$

Lindqvist (1989) had included submersion component in the Equation (2.14) to determine ice resistance working [6]. Based on his observation from the full scale experimental, he conclude that ice would be fractured in the one continue cycle including rotating and sliding of broken ice floes.

$$R_i = \delta\rho . g . h_i \left(T \frac{B+T}{B+2T} + \mu \left(0.7\,L - \frac{T}{\tan\emptyset} - \frac{B}{4\tan\alpha} + T\cos\emptyset . \cos\psi \sqrt{\frac{1}{\sin^2\emptyset} + \frac{1}{\tan^2\alpha}} \right) \right) . \left(1 + 9.4 \frac{v}{\sqrt{g.L}} \right) \tag{2.14}$$

Where $\delta\rho$ is the density difference between the water and the ice, g is the acceleration of gravity, h_i is ice thickness, L , B, and T are the length, breadth and draft of the ship, μ is the frictional coefficient, $\emptyset$ is the stem angle, α is the waterline entrance angle, v is the ship speed in ice and ψ is the angle between the normal of the hull surface and the vertical vector and can be define by ;

$$\psi = arctan \frac{\tan\emptyset}{\sin\alpha}$$

Tan et al. (2013) has rearranged formula of Lindqvist and present coefficients that were applied to represent each of step on the ice breaking including crushing, braking and submersible. That is showed in Equation (2.15):

$$F_x^{ice} = c_h h_i^2 + \left(b_h + \frac{1.4 C_h}{\sqrt{g}} v_x \right) h_i^{1.5} + \left(s_h + \left(\frac{1.4 b_h}{\sqrt{g}} + \frac{9.4 s_h}{\sqrt{g L_{wl}}} \right) v_x \right) h_i \tag{2.15}$$

Keinonen et al. (1996) did research on resistance of five icebreaking vessels in level ice.

$$R_{ice} = C_f \left[0.08 + 0.017 C_s C_h B^{0.7} L^{0.2} T^{0.1} h_i^{1.25} k_1 k_2 \right] \tag{2.16}$$

$$k_1 = \left(1 - 0.0083(t+30)\right)\left(0.63 + 0.00074\sigma_f\right)$$

$$k_2 = (1 + 0.0018(90-\psi)^{1.4})(1 + 0.04(\varphi - 5)^{1.5})$$

Where; R_{ice} is total ice resistance of ship, C_s is water salinity coefficient (0 fresh, 1 saline), C_h is hull condition coefficient (1 inertia, 1.33 bare steel), B, T and L are ship beam at waterline, draft and waterline length in meter, ψ and φ are average flare angle and buttock angle in degree; t is air temperature, σ_f is flexural strength, h_i is ice thickness.

Riska et al. (1997) proposed a level ice resistance formula by modifying the formulations of Lindqvist (1989).

$$R_{ice} = C_1 + C_2 V \tag{2.17}$$

$$C_1 = 0.23 \left(\frac{1}{1 + {}^{2T}/_{B}} \right) B L_{par} h_i + (1 + 0.021\emptyset)\left(4.58 B h_i^2 + 1.47 L_{bow} h_i^2 + 0.29 B L_{bow} h_i\right)$$

$$C_2 = (1 + 0.063\emptyset)\left(18.9 h_i^{1.5} + 0.67 B h_i\right) + 1.55 h_i (1 + 1.2T/B) \frac{B^2}{\sqrt{L}}$$

$$C_f = \frac{1 + {}^{V}/_{\sqrt{g h_i}}}{1 + {}^{V_1}/_{\sqrt{g h_i}}}$$

where V, B, T and L are vessel speed, breadth, draught and length, hi is ice thickness, $\emptyset$ is the stem angle in degrees and L_{bow} and L_{par} are the length of bow and parallel sides section, respectively. C_f is the correction factor considering the effect of vessel speeds with reference speed $V_1 = 1\, m/s$.

Jeong (2010) proposed new ice resistance prediction formula for standard icebreaker model using component method of ice resistance and also predicted the model test results to full-scale using calculated non-dimensional coefficients.

$$R_{ice} = 13.14 V^2 + [0.5\,\Delta\rho g h_i B T]_{\text{buoyancy}} + \left[1.11\,F_h^{-1.157} \rho_i B h_i V^2\right]_{\text{clearing}} + \left[2.73\,S_N^{-1.54} \rho_i B h_i V^2\right]_{\text{breaking}} \tag{2.18}$$

$$F_h = \frac{V}{\sqrt{g h_i}}$$

$$S_N = \frac{V}{\sqrt{\frac{\sigma_f h_i}{\rho_i B}}}$$

JOMAse | Received: 8-April-2017 | Accepted: 30-April-2017 | [(45) 1: 1-8]
Published by International Society of Ocean, Mechanical and Aerospace Scientists and Engineers, www.isomase.org., ISSN: 2354-7065 & e-ISSN: 2527-6085

where R_{ice} is ice resistance, F_h and S_N are Froude number and strength number, α is index of Froude number, β is index of Strength number; ρ_i and ρ_w are ice and water density, $\Delta\rho$ is water density minus ice density, g is gravitational constant, h_i is ice thickness, B and T are beam and draft of the ship, V is ship speed, σ_f is flexural strength of ice.

J.Koto (2002 & 2005) proposed a method to predict ice resistance of a ship sailing in level ice. The method has been applied to double acting tanker Tempera and Mastera. The ice resistance of a ship was derived into submersion (F_{sub}) due to buoyancy, ice-hull friction (F_{frict}), loss of momentum (F_{moment}) due to collision and breaking ice (F_{break}).

$$F_{ice} = F_{sub} + F_{frict} + F_{moment} + F_{break} - F_{thrust} \qquad (2.19)$$

The ice breaking can be written as below

$$F_{break} = \sigma_f . h_i^{\ 2} . f(\emptyset, \alpha) \qquad (2.20)$$

Where; σ_f is Flexural strength of ice, h_i is ice thickness.

Normally in the level ice condition, there are increasing in the submersion resistance which would be coming from fragments of ice. After ship structure interacted with ice, some fragments could be still floating and shear a shape hull of the ship and other fragments were rubbing the bottom of the hull make. Equation (2.21) could be used to determine the submersion resistance with $C_s^{H(Li)}$ to be useable as submersion coefficient in the head level ice condition.

$$F_{sub} = C_{sub} . (\rho_{water} - \rho_{ice}) . g . T . B . h_i \qquad (2.21)$$

Friction resistance which to be calculated in head level ice condition considers some of parameters consist of waterline angle at the fore, stem angle at the bow, dimension of the ship and density of ice, as can be found in Equation (2.22).

$$F_{frict} = F_f^{H(Li)} = C_f^{H(Li)} . \rho_{ice} . g . r . h_i . B . {}^{V}\!\Big/_{\sqrt{L.g}} . f(\emptyset, \alpha, C_w) \qquad (2.22)$$

The resistance due to lose momentum can be written as.

$$F_{moment} = C_{mom} . \rho . B . h_i . V^2 . f(\emptyset, \alpha) \qquad (2.23)$$

3.0 RESULT AND DISCUSSION

In the study, ice resistances of MT Uikku, Helay and Araon are calculated by empirical and analytical formulas proposed by Lindqvist, Keinonen, Riska, Jeong annd J.Koto and compared with experimental test results.

The icebreaking tanker MT Uikku is a double-hull icebreaking motor tanker that is owned by Neste Shipping and Kvaerner Masa-Yard's joint venture company, Nemarc. Table 1 shows the principal dimensions of MT Uikku.

Figures 3 and 4 show comparison of ice resistance of MT Uikku from experiment and calculation using various formulas at 0.63 m and 1.04 m ice thickness, respectively. The error between measured data and analytical data was also calculated as shown in Table . It shows that the calculated ice resistance using Riska formulas overestimate up to 46% in average and the Riska formula also gave the largest predictions among all formulas. Joeng formulas estimate ice resistance with the difference of 12%. Konenien formulas overestimate the ice resistance by 48% in average. The average error of Koto formula was very well with 4.7 % in average.

Table.2: Principal dimenison of the icebreaker MT Uikku [Hu, 2016]

Scale (λ = 31.56)	Model	Full
Length between perpendicular (m)	4.75	150.0
Length of bow (m)	1.24	39.0
Length of parallel (m)	2.06	65.0
Beam (m)	0.67	21.3
Draft (m)	0.30	9.5
Stem angle (deg)	30.0	30.0
Waterline enrance angle (deg)	21.0	21.0

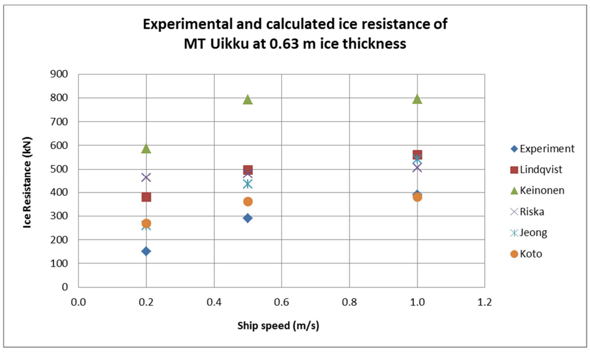

Figure 3: Comparison of experimental and calculated ice resistance of MT Uikku at 0.63 m ice thickness.

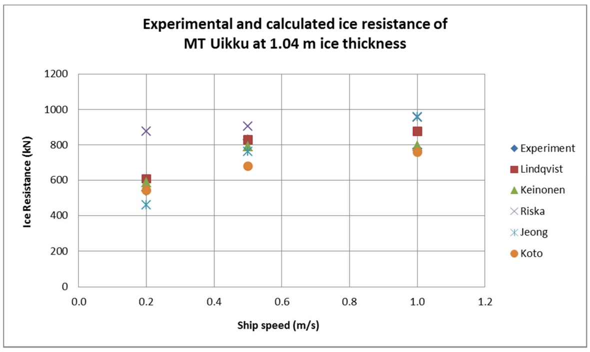

Figure 4: Comparison of experimental and calculated ice resistance of MT Uikku at 1.04 m ice thickness.

Table.3: Average error of empirical formula for prediction ice resistance of MT Uikku.

Formulas	Average error %
Lindqvist	36.4
Keinonen	48.4

JOMAse | Received: 8-April-2017 | Accepted: 30-April-2017 | [(45) 1: 1-8]
Published by International Society of Ocean, Mechanical and Aerospace Scientists and Engineers, www.isomase.org., ISSN: 2354-7065 & e-ISSN: 2527-6085

Riska	46.0
Jeong	12.0
J.Koto	3.1

Table.4: Principal dimenison of the icebreaker Healy [Jeong, 2017]

Scale (λ = 23.7)	Model
Length between perpendicular (m)	5.10
Beam (m)	1.05
Draft (m)	0.36
Stem angle (deg)	32.0
Waterline enrance angle (deg)	24.0
Block coefficient (C_B)	0.583
Midship coefficient (C_M)	0.898
Waterline are coefficient (C_W)	0.818
Displacement (kg)	1240

Figures 5 and 6 show comparison of ice resistance of icebreaker Healy from experiment and calculation at 0.40 m and 0.58 m ice thickness respectively. It shows that the calculated ice resistance using Jeong formulas underestimate up to 69% in average as shown in Table 5. The Riska formula estimate ice resistance with the difference of 27% in average. The average error of Koto formula was the lowest with 11 % in average.

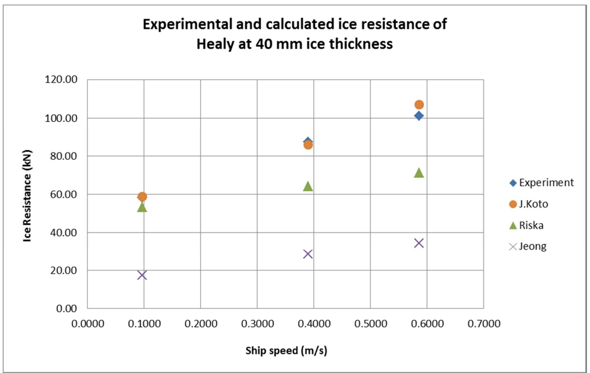

Figure 5: Comparison of experimental and calculated ice resistance of icebreaker Healy at 40 mm ice thickness.

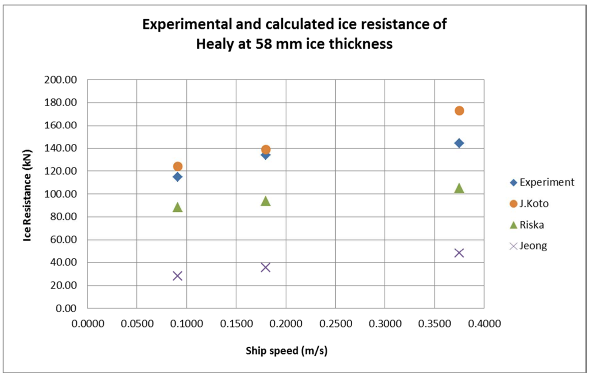

Figure 6: Comparison of experimental and calculated ice resistance of icebreaker Healy at 58 mm ice thickness.

Table.5: Average error of empirical formula for prediction ice resistance of icebreaker Healy.

Formulas	Average error %
Riska	27.0
Jeong	69.0
J.Koto	0.3

Table.6: Principal dimenison of the icebreaker Aaron [Jeong, 2017]

Scale (λ = 18.67)	Model
Length between perpendicular (m)	5.10
Beam (m)	1.02
Draft (m)	0.364
Stem angle (deg)	35.0
Waterline enrance angle (deg)	54.3
Block coefficient (C_B)	0.603
Midship coefficient (C_M)	0.898
Waterline are coefficient (C_W)	0.923
Displacement (kg)	1142

Figures 7 and 8 show comparison of ice resistance of icebreaker Araon from experiment and calculation at 29 mm and 53 mm ice thickness, respectively. It shows that the calculated ice resistance using Jeong and Riska formulas underestimate up to 48% and 50 % in average, respevtively, as shown in Table 7. The average error of Koto formula was the lowest with 8 % in average.

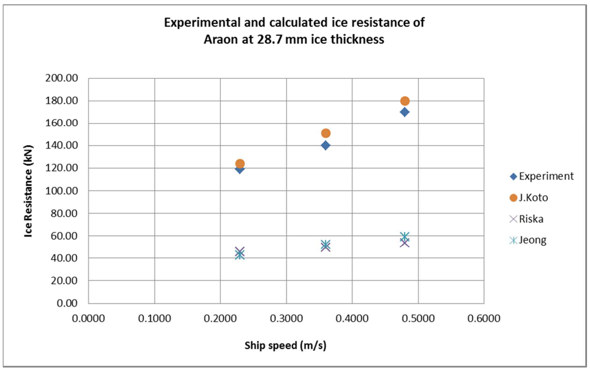

Figure 7: Comparison of experimental and calculated ice resistance of icebreaker Araon at 28.7 mm ice thickness.

JOMAse | Received: 8-April-2017 | Accepted: 30-April-2017 | [(45) 1: 1-8]
Published by International Society of Ocean, Mechanical and Aerospace Scientists and Engineers, www.isomase.org., ISSN: 2354-7065 & e-ISSN: 2527-6085

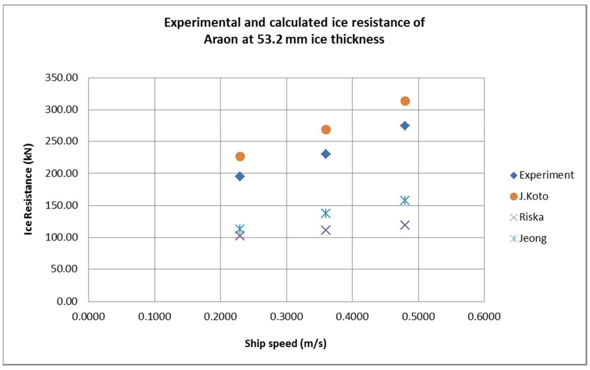

Figure 8: Comparison of experimental and calculated ice resistance of icebreaker Araon at 53.2 mm ice thickness.

Table.7: Average error of empirical formula for prediction ice resistance of icebreaker Araon.

Formulas	Average error %
Riska	50.0
Jeong	48.0
J.Koto	0.4

Figure 4.6 showed ice resistance acting on Double Acting Tanker in the function of velocity of the ship. The ice resistance predicted is for the condition where the ship running ahead in level ice condition at 0.5 m ice thickness.

3.0 CONCLUSION

In conclusion, this paper has discussed a method to predict resistance of a ship in level ice. The methods are verified using experimental data. The method was also compared with other empirical methods: Lindqvist, Riska, Keinonen and Jeong. It was founded that the average errors using the proposed method was 3 % for MT Uikku, 0.3 % for Hellay and 0.4 % for Araon.

ACKNOWLEDGEMENTS

The authors would like to convey a great appreciation to Ocean and Aerospace Engineering Research Institute, Indonesia and Universiti Taknologi Malaysia for supporting this research.

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Published by International Society of Ocean, Mechanical and Aerospace Scientists and Engineers, www.isomase.org., ISSN: 2354-7065 & e-ISSN: 2527-6085

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