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Modelling of ship resistance in compressive ice channels

Reino Külaots [1], Pentti Kujala [1], Rüdiger von Bock und Polach [1], Jakub Montewka [1]
[1]Aalto University, Espoo, FINLAND

ABSTRACT

The effect of compressive ice fields on the resistance and performance of ships has been a research topic for a few decades, but still the knowledge is limited on this subject. This paper presents an empirical model for estimating the resistance of a general cargo ship in the compressive ice channel, which can be a case for ships navigating in convoy, following an icebreaker. The model is based on the findings from model scale tests carried out in the ice tank at Aalto University, for a bulker - 1A Super ice class (FSICR). Through the tests, an additional resistance component in a compressive case was discovered. It is assumed that it comes from the pressure of moving ice rubble collected below the ice sheet on the sides of the ice channel and it has not been accounted for in other models. This in turn creates significant added resistance for a ship if the ice channel, she navigates in, is closing, because of ice compression. The model which is introduced considers different resistance components as follows: the level ice resistance due to a closing channel, the channel resistance and added resistances due to level ice compression and the newly discovered resistance caused by ice rubble compression on the sides of the ice channel. The results show that, the general principle adopted for modelling the ship resistance in ice and the methods used for calculating individual components of the resistances give fairly accurate results, when compared with the model test results. The model which is obtained allows for fast prediction of the resistance level of a cargo ship with a long parallel midship section in various ice conditions, which can be further utilized for modelling ship transits in ice.

INTRODUCTION

For the countries around the Baltic Sea winter navigation is important for several months of the year and therefore they operate one of the world's largest ice-breaker fleet combined. Power requirements for commercial vessels are based on ice channel resistance and therefore it has been well investigated. For ice-breakers one of the most important characteristics is level ice breaking capability and penetration through ridges. Ridges are formed due to dynamic ice fields and these ice fields pose great threat to regular ships. Ships navigating in dynamic ice fields may experience a considerably higher resistance due to compression in ice, great enough for them even to get stuck (Eriksson, et al., 2009). This in turn may lead to structural damages of the ship and there is a great risk for the vessel to run aground while drifting with the ice field. In order to avoid these kinds of situations and to improve the knowledge about compressive ice fields, an EU project called SAFEWIN has been launched. The aim of the project is to develop a forecasting system for compressive ice. If this is achieved the ships navigating in the Baltic Sea can be informed of potentially hazardous regions as compressive ice fields tend to be a localized phenomenon. This paper attempts to give a simplified approach to estimate the resistance that ships encounter in compressive ice channels.

State of art

Compressive ice fields have been a research subject for some decades, but still the knowledge about the effect on ships and trafficability is limited. One of the first research projects in this field was „A Ship in Compressive Ice“ (Riska, et al., 1995) which was a joint project between Laboratory of Naval Architecture and Marine Engineering of Helsinki University of Technology and the Institute of Problems in Mechanics of Academy of Sciences in the former USSR. The project was carried out in the beginning of 1990's. Valuable data was collected through model tests and full scale observations. Different theories were developed during the project, which are still in use today. For the project summary refer to (Riska, et al., 1995).

Keinonen, et al. (1996) presented an icebreaker escort model for evaluating the performance and efficiency of transit of various commercial vessels navigating alone and also when assisted by an icebreaker in different ice conditions. They introduced the term equivalent ice thickness, also known as effective ice thickness, which means that separate ice conditions are represented by a layer of level ice thickness to enable evaluation with only one formula. The main need for this kind of representation is that sea ice has highly variable properties and this helps to generalize the conditions for simpler transit simulations. The concept of equivalent ice thickness is presented in Figure 1.

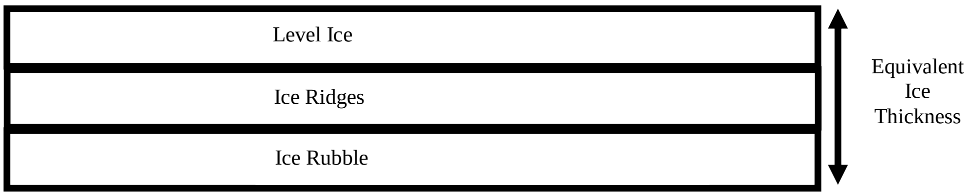

Figure 1. Concept of equivalent ice thickness according to Keinonen, et al.

Keinonen, et al. (1996) also included the ice compression into the analysis through very general coefficients for the equivalent ice thickness, but these were loosely defined.

Riska, et al. (2006) conducted model tests in various ice conditions, which included level ice, ridges and compression. Based on the analysis of the results they presented a general transport study for year round navigation of a tanker ship. A generalized formula for estimating ship resistance in different ice conditions, including compressive ice, was presented.

Kaups (2012) developed a calculation method to evaluate the added resistance to the ship through the forces created on the parallel midship section in level ice by the converging ice fields. The model was validated using a case study made during the SAFEWIN project about the Double-Acting Tankers (DAT) MT Mastera and MT Tempera. This case study used the ice forecast model Polar View data, which was developed in Finnish Meteorological Institute (FMI), as input for the calculation model and compared the speed reduction to the Automatic Identification System (AIS) data. The calculation model underestimated the performance of the tankers, but that was explained by the fixed properties of ice used in the calculation model, the actual ice conditions vary and the exact ice conditions, which the ships were in at the time, are unknown. Kaups (2012) compared the calculation method to the model test data from the project "A Ship in Compressive Ice" (Riska, et al., 1995) and found a fair agreement.

During the SAFEWIN project model testing with a similar setup to those conducted during the "A Ship in Compressive Ice" project (Riska, et al., 1995), were performed in the ice model test basin of Aalto University (Suominen & Kujala, 2012). The measurements included towing force, total force on the parallel ship side and ice pressure using two tactile sensor sheets, one in the bow shoulder and one in the parallel midship. These tests were conducted in level ice, newly broken channel, compressive level ice and closing compressive channels with different ice thicknesses and ice drift speeds. The model towing speed was kept constant. A correlation between ice drift velocity and measured resistance was observed. In the previous projects the resistance of a vessel in a compressive ice channel has not included the added resistance due to ice rubble compression in the evaluation of total resistance. The main resistance components in a compressive ice channel have been considered to be the channel resistance from the brash ice and the added resistance due to level ice compression from the contacts on the parallel midship section of the vessel (Eriksson, et al., 2009), neglecting the resistance due to brash ice compression.

Channel resistance

The minimum power requirements in the Finnish-Swedish Ice Class Rules (FSICR) are derived from a calculation procedure developed by Wilhelmson (1996) for estimating the resistance of ships in brash ice channels. Wilhelmson's (1996) calculations rely on soil mechanics and the internal friction of the brash ice mass. The calculation method was validated using model tests. The most important parameter for his procedure is the ice channel thickness in the middle of the channel. In this paper the method proposed by Wilhelmson is used to calculate the channel resistance component.

Added resistance due to compression in level ice

A semi-empirical model for estimating the added resistance due to compression in level ice has been developed at Aalto University; see (Kaups, 2012). In the model a simplified breaking pattern of the ice is used to calculate contacts of the ship's parallel midship with the ice field. The model adopts the assumptions made by Riska et al. (1995) that the ice breaking pattern in the bow does not change in a compressive situation and the additional resistance is related to the parallel midship where the drifting ice will have contacts with the hull. The assumption is illustrated in Figure 2.

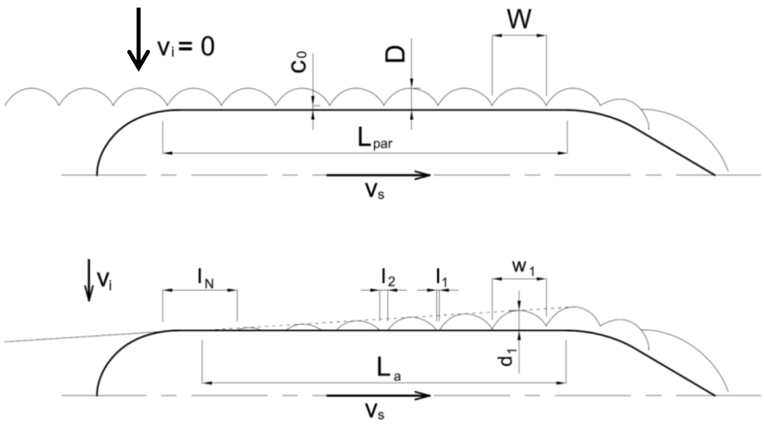

Figure 2. Simplified ice breaking pattern at ice velocity equal to zero and ice velocity higher than zero (Kaups, 2012)

The ice is assumed to break in cusps and due to a transversal velocity of the ice field the cusp edges will start to have contact with the side of the ship, which creates an additional drag. The contact areas are estimated through the ice thickness and relative velocities of the ice field and the ship. The pressure created by these contacts is evaluated using a crushing pressure-nominal contact area relationship which was defined by Kujala and Arughadhoss (2012). This design envelope was obtained from various ice crushing tests such as model tests with MT Uikku and a general cargo ship as well as observations done on board IB Sampo and studies published earlier. The pressure-area design envelope has the following form (Kujala & Arughadhoss, 2012):

$$P = 0.42 \cdot A^{-0.52}, \tag{1}$$

where A is the nominal contact area [m^2] and P the resulting pressure [MPa] on that area.

The normal forces created in these contact areas are summed up and the added resistance due to level ice compression is calculated through the frictional force (2):

$$R_{comp} = \sum_{i=0}^{n} 2 \cdot N_i \cdot \mu_h, \tag{2}$$

where N_i is the i-th normal contact force and μ_h is the friction coefficient between hull and ice.
Simplifications made by Kaups (2012) limit the usage of the calculation method to ships with long parallel midship sections without inclined sides, such as tankers and bulk carriers. Secondly the breaking pattern is simplified enough to enable the representation of ice cusps only with two parameters and the ice rubble trapped inside the cusps (Figure 3.) is assumed not to produce additional resistance. Furthermore, since the sides of the vessel are considered to be transversal to the waterplane in the contact zones, the bending and buckling failure of ice is neglected and only crushing of the ice is assumed to be taking place. One of the most important simplifications when considering real-life conditions is that the ice is assumed to have a constant thickness.

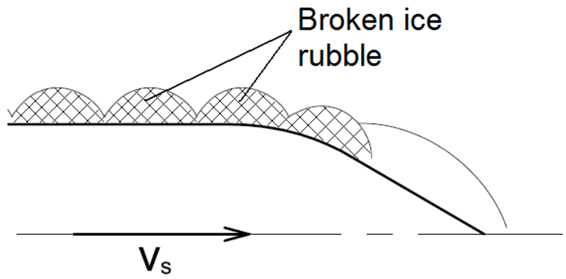

Figure 3. Rubble stuck in cusps (Kaups, 2012)

METHODS

In order to investigate the assumptions made for using different calculation methods for evaluating the model testing resistance, one additional test series was conducted for the SAFEWIN project. The objective was to determine the different resistance components present in different ice conditions to be able to evaluate them separately by using known methods. It was assumed that the different resistance components are independent from each other and therefore they can simply be summed up to obtain the total resistance. The calculation methods include ice resistance components only. The model tests were conducted only at one velocity and therefore open water resistance is not evaluated but rather a test result for open water resistance was used.

The tests were conducted in the ice basin of Aalto University. The model ice in the basin is granular ice of ethanol solution (Jalonen and Ilves, 1990). The model ice is produced by spraying droplets of the water-ethanol solution into cold air from the nozzles on the bridge, which moves back and forth over the basin. The droplets cool down and drop onto the surface of the basin, forming slush ice (Suominen & Kujala, 2012). This procedure is continued until target ice thickness is reached. After spraying the ice properties are achieved with tempering the ice cover where the temperature is decreased below -15 [°C].

Before the test runs the properties of the ice cover are measured. In order to avoid the towing line to fall slack, it was decided to equip the model with another load cell in the aft of the model which is connected to a line that is used for braking the model. The difference between the two measured loads in the fore and aft load cells is the resulting total resistance of the model. The general testing setup is presented in Figure 4.

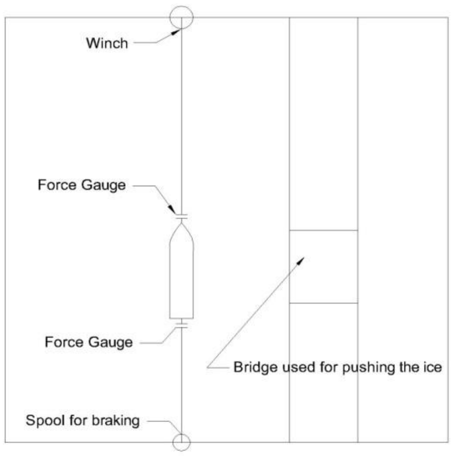

Figure 4. Schematic for the test setup

Test plan

The test series consisted of 12 tests altogether. The tests were done in level ice (2), open channel (1), open compressive channel (3), half closed non-compressive channel (2) and closed compressive channel (2). In addition one test was conducted in rafted ice and one test as a pure brash ice channel resistance test.

RESULTS

The measured ice properties are presented in Table 1. Only the relevant measured average resistances for this paper are presented in Table 2 and a time history can be found in Figure 5. The resistance level is relatively stable after the initial acceleration. The friction coefficient between the hull and ice was measured and a value of 0.08 was obtained.

Table 1. Measured model ice properties

Property	Value	Unit
Thickness	31	mm
Compressive strength σ_c	46.8	kPa
Bending strength σ_b	14.9	kPa
Elastic modulus E	4.7	MPa

Table 2 Model testing results

Test type	Ice velocity [m/s]	Test number	Resistance [N]
Open channel	0	Test2	18,7
Comp. channel	5mm/s	Test3	109,0
Comp. channel	5mm/s	Test5	178,2
Comp. channel	5mm/s	Test11	199,7

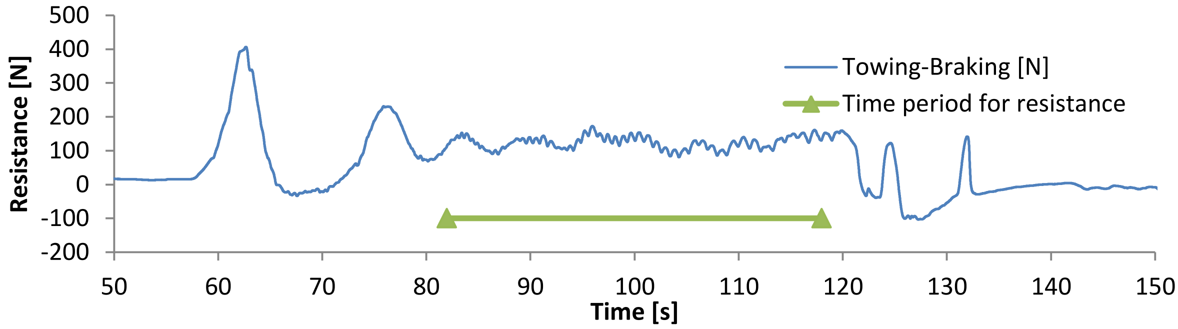

Figure 5. Time history from test 3, ice velocity 5[mm/s]; zero level for resistance at 15N

ANALYSIS

During the tests an additional component of resistance was observed in compressive open channel tests (tests 3, 5 and 11). The only changing variable in the different tests was the amount of ice rubble below the level ice. To take this into account, the volume of ice rubble on the sides of the channel, under the level ice, was calculated for a cross-section of the channel, see Table 3 and Figure 6. It was assumed that the volume of the ice rubble created by the ship model comes from the level ice broken by the model in the channel and 90% of this rubble is trapped under the sides of the ice channel. This was possible due to the fact that the model was pulled back every time after each test run and most of the ice rubble was displaced to the sides of the channel. The bridge, which was used to push the ice to create a compressive situation, was kept immobile after each test. The total volume of the ice rubble was assumed to be constant with a saturation level μ_b of 0.6 (Wilhelmson, 1996). By calculating the amount of ice rubble under the sides of the channel and using the slope angle presented by Wilhelmson (1996), the contact height is approximated. It is assumed that the contact with the model occurs at every time instance in a similar cross-section and there has not been enough time for the ice rubble to spread too far from the channel. The compressive open channel tests were conducted at a very low compression with ice velocity of 0.005 [m/s]. Therefore the conditions are assumed to be quasi-static throughout the test. A sketch of the contact instance is presented in Figure 6. The added resistance due to level ice is estimated using the calculation method proposed by Kaups (2012).

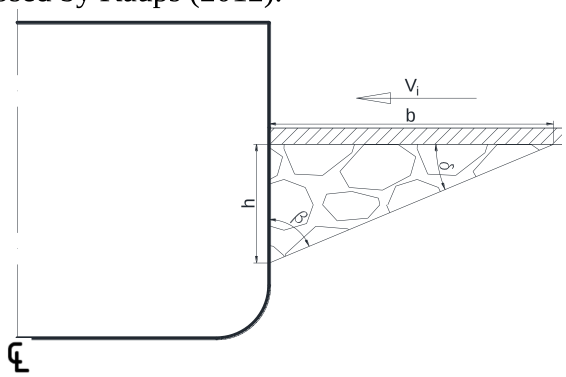

Figure 6. Estimation of contact height with ice rubble in an open channel.

The distribution of the ice rubble is assumed to be symmetric with respect to the centerline of the model, therefore the calculations are done only for one side and the total added resistance is multiplied by a factor of two in the final calculation. The angle δ adjacent to b of the triangular cross-section of the ice rubble is 22.6 [deg] and the angle between the ship hull and level ice is 90 [deg], thus the third angle β can be calculated from β=180-90-22.6= 67.4 [deg]. The area of the triangular cross-section can be evaluated using formula (3):

$$A = \frac{b^2(\sin(\delta)(\sin(\delta+\beta))}{2\sin(\beta)}, \tag{3}$$

where b is the side which is in contact with the level ice, δ is the slope angle, and β is the angle in the lower corner. b is derived from equation (3):

$$b = \sqrt{\frac{A \cdot 2\sin(\beta)}{(\sin(\delta)(\sin(\delta+\beta))}}. \tag{4}$$

The height in contact can be calculated using formula (5), which is derived from the basic triangle area calculation formula:

$$h = \frac{2A}{b}. \tag{5}$$

By knowing the height which is in contact with the ship, the total area can be estimated through the parallel midship length, as this is the most probable part in contact with the ice rubble. A pressure is assumed to be present in the ice rubble due to its natural behavior as it would spread if there was no ship stopping it and also due to the motion of the level ice and internal friction of the brash ice mass. The pressure is assumed to be uniformly distributed over the contact area. The added resistance from the brash ice is calculated using equation (6):

$$R_{rub} = 2\mu_h \cdot P_{rub} \cdot h \cdot L_{par} \cdot f, \tag{6}$$

where μ_h is the hull frictional coefficient, P_{rub} is the pressure of the rubble taken as 310-520 N/m^2, based on the findings of Keinonen & Nyman (Mellor, 1980). The pressure is velocity dependent, but the velocity of the ice is very low in the tests and therefore the condition can be assumed quasi static. h is the calculated height of the rubble contact, see Figure 6 which is limited by the draft T and level ice thickness. L_{par} is the parallel midship length, f is a factor to take into account the fact that the parallel midship is not a perfect rectangle, but a function of draft. For this paper and analysis of model tests, it is estimated from the lines drawing of the vessel and it is taken as 0.85.

Comparison to model testing results

The volumes of brash ice used in the calculations are given in Table 3 and the comparison to measured model testing resistances is presented in Table 4. As the brash contact height of ice is calculated from the cross-sectional area, the brash ice volume is presented as volume per unit length.

Table 3 Brash ice volumes and contact heights used in the calculations

	Volume [m^3/m]	Breadth of ice rubble (b) [m]	Contact Height (h) [m]
Test 3	0.023	0.334	0.139
Test 5	0.068	0.572	0.238
Test 11	0.184	0.941	0.319

As a comparison the total resistance is also calculated using a formula proposed by Riska (2006). The line load used in the formula was obtained during the course of the model tests conducted by Suominen (2012) and has the following form (Lehtonen, 2012):

$$q = 205.7 l^{-0.26}, \tag{7}$$

with the length l [m] and line load q [N/m].

For tests 3 and 11 the calculated total resistance includes the measured open channel resistance, which is assumed to account for the open water resistance, added resistance due to level ice compression and the added resistance due to brash ice compression, equation (6). The small amount of brash ice, which was in the channel during test 2 (the open channel test) is assumed to account for the absence of turbulence stimulators. For test 5 also the channel resistance component is included as the channel was partially covered with ice rubble during the test. The ice rubble thickness in that test is assumed to be the same as the measured level ice thickness, which was 31mm.

Table 4 Model testing results compared to calculation model

	Measured Resistance	R_{total} (P_{rub} 310 [N/m^2])	Relative Difference	R_{total} (P_{rub} 520 [N/m^2])	Relative Difference	R_{total} (Riska 2006)	Relative Difference
Unit	[N]	[N]	-	[N]	-	[N]	-
Test 3	109.0	90,32	-17 %	108,38	-1 %	123,53	13 %
Test 5	178.2	133,22	-25 %	164,13	-8 %	147,46	-17 %
Test 11	199.7	124,79	-38 %	166,19	-17 %	123,53	-38 %

Sensitivity analysis of the proposed method

The aim of the sensitivity analysis is to determine the effect of changes in the model input parameters to the model output. The model is described by Equation 6, where the output is the added resistance from the brash ice and the following input parameters are considered: the slope angle of the ice rubble δ, pressure of the ice rubble (P_{rub}), factor for the contact area shape (f), and the hull-ice friction coefficient (μ_h). It is assumed that the added resistance due to brash ice compression can be calculated using the principles of superposition, thus the average resistances for the tests in Figure 7 are obtained by subtracting open channel resistance (test 2) and calculated added resistance due to compression in level ice (Kaups, 2012) from the measured average model testing resistance.

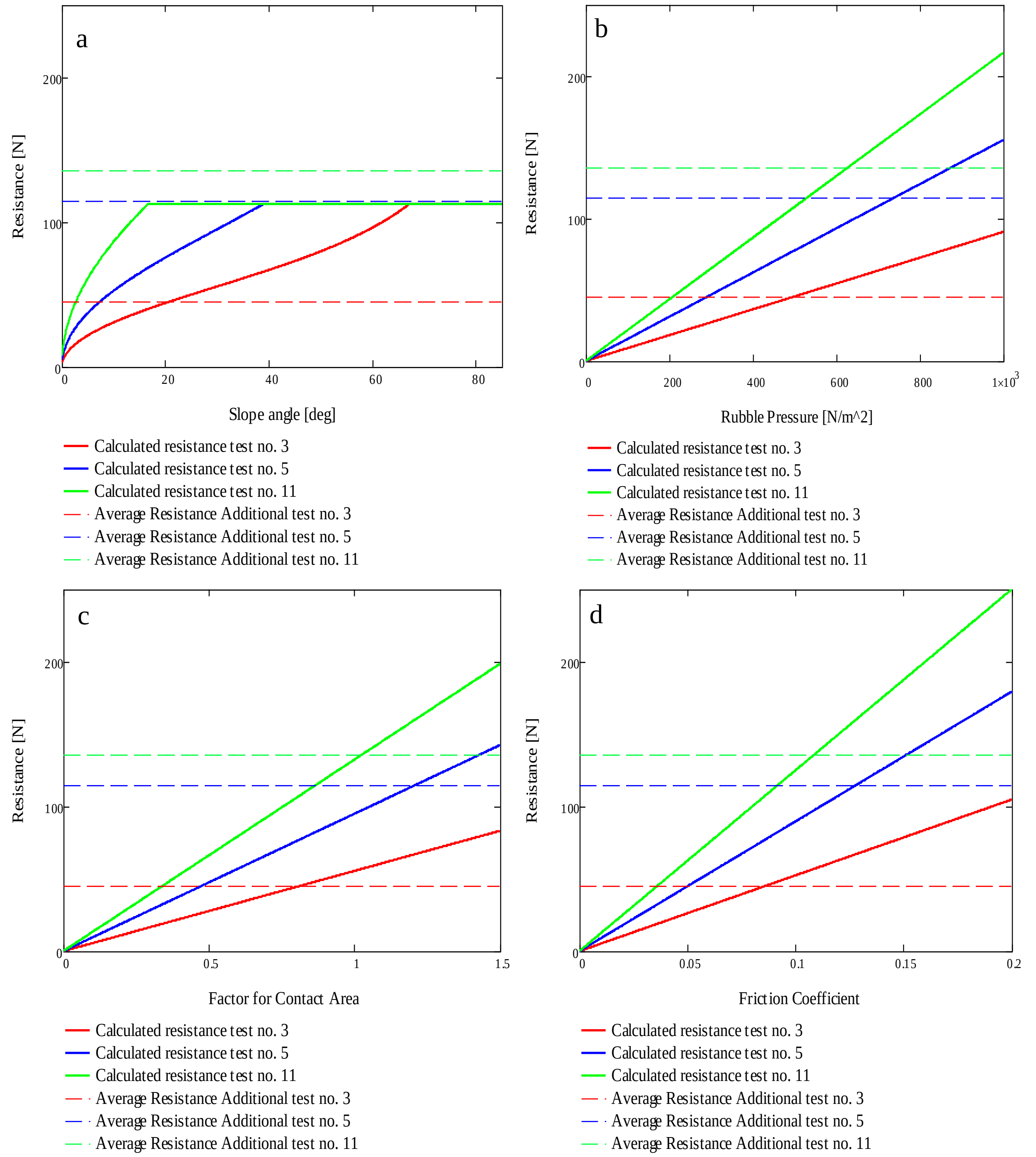

Figure 7. Influence of slope angle of the ice rubble (a), rubble pressure (b), factor for contact area(c) and friction coefficient (d) on the calculation model and comparison to average model testing resistances

The average resistances due to brash ice compression for different tests are used as the reference level for the sensitivity analysis. The graphical representation of the different parameters and their effect on the total resistance is presented in Figure 7. The used values in the tests are 22.5 [deg] for slope angle δ, 520 [N/m^2] for rubble pressure P_{rub}, 0.85 for the factor for contact area f and 0.09 for the friction coefficient μ_h.

A method for evaluating total ice resistance in a closing compressive channel.

In the SAFEWIN testing the tested ship model was observed to experience an additional breaking component due to the level ice in the closing channel. Thereby the assumption is made that the additional breaking component due to level ice is linearly increasing throughout the test when the channel is closing in front of the model, see Figure 8. This is taken into account through estimating the level ice resistance for a half-closed channel.

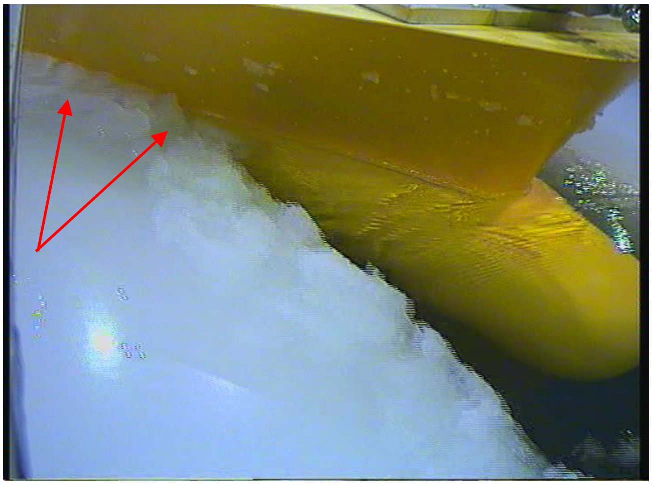

Figure 8. Effect of channel closing is creating an additional ice breaking component due to level ice.

In the SAFEWIN tests the velocities of the ice were greater than that of in the tests described in this paper and the proposed method for evaluating total ice resistance is mainly based on the findings from those tests. Finally, the assumption is that all the components are considered independent and can therefore be summed up to estimate the total resistance, which takes the following form:

$$R_{total} = R_{ice}(B_{channel}) + R_{ch} + R_{comp} + R_{rub}, \qquad (8)$$

where R_{ice} is level ice resistance component, which is estimated using Lindqvist (1989) method, the breadth $B_{channel}$ of the closing channel is taken into account linearly, R_{ch} is the channel resistance component, which is estimated using formula Wilhelmson's (1996) method, R_{comp} is the added resistance due to compression from level ice, which is estimated using the method proposed by Kaups (2012) and R_{rub} is estimated using Equation (6) introduced in this paper. For the detailed description of the method the reader is referred to Külaots (2012).

DISCUSSION

The open compressive channel tests revealed an additional resistance component, which is associated with the amount of ice rubble trapped under the ice sheet. By investigating this issue a new method for calculating ship resistance in compressive ice channel is proposed. Notwithstanding all the assumptions made in this paper, the calculated resistance is within 10% range for the measured resistance of two out of three tests. Possibly the third test resistance is higher due to the increasing ice rubble pressure as the volume and also mass of the ice rubble increase. This assumption is backed up with the measurement data from the midship load panel for different tests (Külaots, 2012). As the contact height of the model is limited between the level ice thickness and draft (bottom) of the vessel, a limit in the resistance is reached for every test, when changing the slope angle. As expected the pressure of ice rubble influences the calculation model linearly. The influence of the friction coefficient is the highest. The factor for scaling the contact area has the lowest influence on the calculation model. The slope angle has an influence, but the change of this factor cannot be high in reality as different authors have observed a very similar angle to the chosen one (Wilhelmson, 1996). The volume of ice which is assumed to be trapped under the ice has a high influence, as can be seen from the different tests, which are included in this analysis. Naturally the volume of ice is one of the most uncertain factors in the whole calculation, followed by the pressure of ice rubble. The volume of ice trapped under the level ice sheet is directly affecting the contact height according to the calculation formula (5). The actual distribution of the ice rubble is not known, as it was not measured and the ship model has been towed back and forth many times during the testing series. In addition, the closing of the channel in between the tests created a new distribution for the ice rubble, as well as, the rafted ice test. The mechanical covering of the ice channel with ice rubble for the channel test also affects the distribution significantly, as the ice rubble was brushed from the sides of the channel into the middle of the channel to achieve a relatively homogenous distribution of the ice rubble and the thickness of the ice rubble. Nevertheless, the proposed method delivered fair agreement. However, there is a bias towards under-estimation of the total resistance in some of the calculations (Külaots, 2012).

As an alternative simulating method, a combined finite-discrete element method (FE-DEM), as described by Paavilainen (2013) could be used to model the ice rubble behavior and forces inflicted to the side of the ship hull. Although the method is time consuming for current computers (Paavilainen 2013), the results of the methods could be cross-compared as good correlations were found with experimental data for sloping structures (Paavilainen 2013).

CONCLUSIONS

Model tests have been performed and an additional resistance component for ships in compressive ice has been discovered through the experiments. An explanation and a calculation method for estimating added resistance due to brash ice in a compressive situation has been proposed, which is then included into a calculation formula, which combines different ice resistance components. The calculation approach revealed good results for the resistance of various ice conditions, compared to model test results. The proposed calculation method, backed up by the model tests, shows that the ice rubble has a great influence on the total resistance of a ship in a compressive ice channel.

ACKNOWLEDGMENTS

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