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Teemu Heinonen

AN EXPERIMENTAL STUDY ON THE EFFECT OF SPEED ON THE ICE RESISTANCE OF A SHIP

Phase II for Winter Navigation Board

Finnish Transport Safety Agency

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FOREWORD

In its report no 74, The Winter Navigation Research Board presents the outcome of the phase II of the project on an experimental study on the effect of speed on the ice resistance of a ship.

In recent years maritime administrations in the Baltic Sea region have started to emphasize the need for higher escort speeds in ice, typically recent requirement definitions have been 12 to 13 knots. This would provide more fluent traffic. On the other hand, the effects of speed on the ice breaking process are poorly known and there has been some indications that ice model tests do not work well at speeds above 10 knots. Therefore more knowledge about ice breaking process is needed.

The Winter Navigation Research Board warmly thanks Mr. Teemu Heinonen for this report.

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An experimental study on the effect of speed on the ice resistance of a ship

Phase II

for

Winter Navigation Board

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1. INTRODUCTION AND TEST PROGRAM

In recent years maritime administrations in the Baltic Sea region have started to emphasize the need for higher escort speeds in ice, typically recent requirement definitions have been 12 to 13 knots. This would provide more fluent traffic. On the other hand, the effects of speed on the ice breaking process are poorly known and there has been some indications that ice model tests do not work well at speeds above 10 knots. Therefore more knowledge about ice breaking process is needed.

The effect of speed for the ice resistance of a ship was studied experimentally by Heinonen (2010). Ice model tests were performed both at Aalto University and at Aker Arctic Technology Inc. These tests are presented in the Phase I report (Heinonen 2010).
Unrealistically high ice resistances were measured on the model tests of Phase I. In the report of the Phase I it was concluded that the high ice resistance could be due to the fact that the model ice is not brittle enough and also that the broken ice pieces stick onto the bow as it is submerged and form a slow moving layer of ice against the bow.
This report covers the phase II model tests which were conducted on the basis of the Phase I. Tests are presented on chronological order as the outcome of the tests affected which tests were performed next. A summary of phase II tests is presented in Table 1-1. All tests were towing tests without propulsion in level ice.

Table 1-1: Tests conducted in phase II.

#	Date	H_i [mm] m.sc.	H_i [m] f.sc.	σ_f [kPa] m.sc.	σ_f [kPa] f.sc.	Performed tests
1	30.09.	15	0.3	27.5	550	Less saline ice; speed 1.84 m/s (16 kn in f.sc.)
2	01.10.	15	0.3	27.5	550	Normal ice; speeds 0.69 & 1.38 m/s (6 & 12 kn in f.sc.)
3	15.12.	15	0.3	27.5	550	Normal ice; model equipped with turbulence stimulator; speed 1.38 m/s (12 kn in f.sc.)
4	22.12.	15	0.3	50	1000 (scaled down to 550)	Flexural strength twice the normal and scaled down; model equipped with turbulence stimulator; speed 1.38 m/s (12 knots in f.sc.)

2. THE MODEL

The model of IB Otso was used in all tests. IB Otso was chosen for the tests as there is lot of previous data and test results for it (both full-scale and model-scale). Also full-scale tests of Phase I were done at IB Kontio which is the sister ship of IB Otso.

The model is built from glass fibre and the scale is 1:20. The main particulars of the model and ship are presented in Table 2-1. Photographs of the model are presented in Figure 2-1 through Figure 2-3.
The surface of the model was treated in accordance with the AARC standard methods. The target friction coefficient between the surface and the ice was 0.050**.** The friction coefficient and surface roughness of the model has been measured as a part of other tests (for example Manderbacka et al. 2010) and it is close to the target value and therefore cannot explain the high resistance.
The model had no propellers as the model was towed in all tests. The model was otherwise the same in all tests except in tests at 15.12. and 22.12.2010 the model was equipped with a turbulence stimulator (Figure 2-5 and Figure 2-6). The stimulator was made from 0.6 mm thick welding wire which was attached to the bow with two layers of tape. Thickness of the tape was 0.4 mm and the width of the first layer was 2.4 cm and the second 4.7 cm. The dimensions of the stimulator are presented in Figure 2-4. The size of the stimulator was small and it was below the waterline. It was assumed that in this manner the turbulence stimulator would not affect the breaking of the ice and the ice pieces itself would not stick considerably into the stimulator.

Table 2-1: Main particulars of the model and ship

	Ship	**Model**
L_{DWL} [m]	90	4.5
Breadth [m]	23.35	1.17
Draught [m]	7.3	0.365

Figure 2-1: The bow of the model. The turbulence stimulator is intact on the bow.

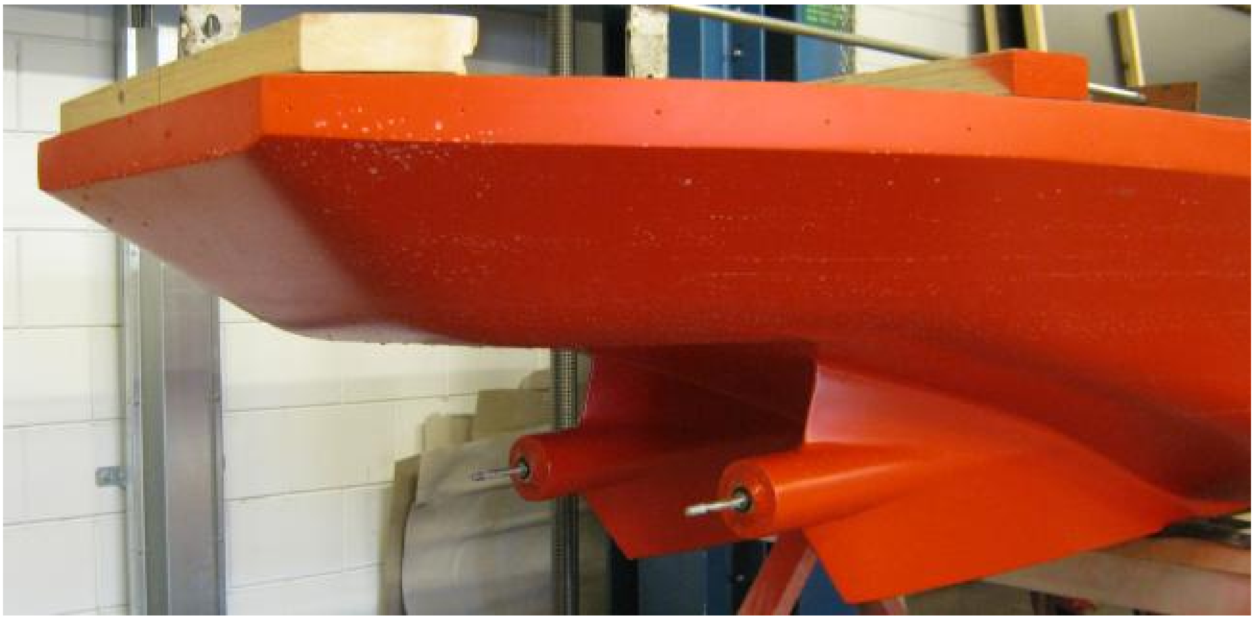


Figure 2-2: The stern of the model. No propellers were used.

Figure 2-3: Side view of the model.

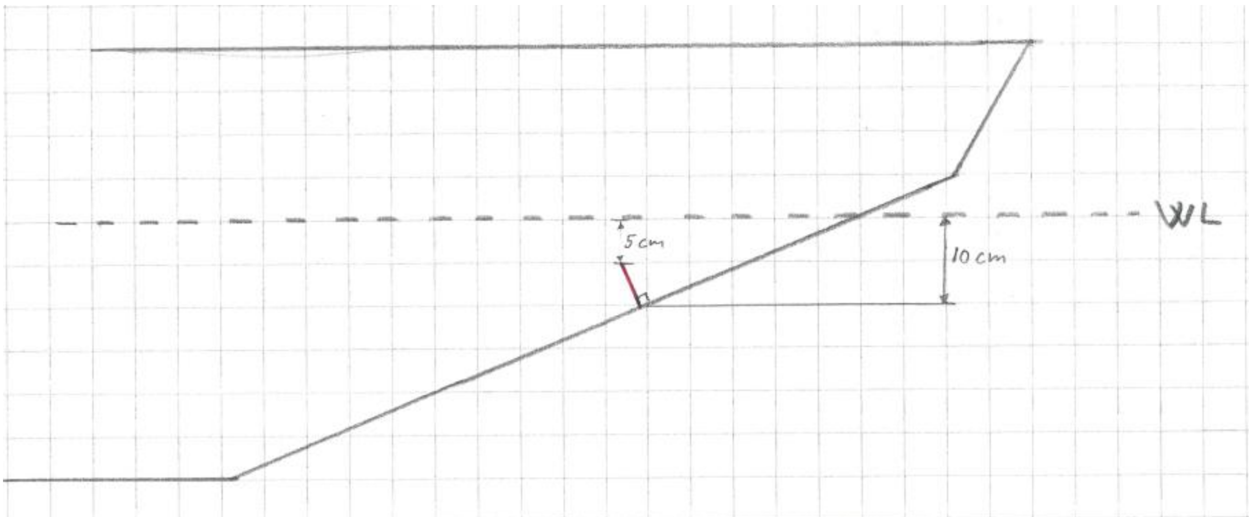


Figure 2-4: The position of the turbulence stimulator (marked with a red line). The picture is not in scale.

Figure 2-5: The turbulence stimulator.

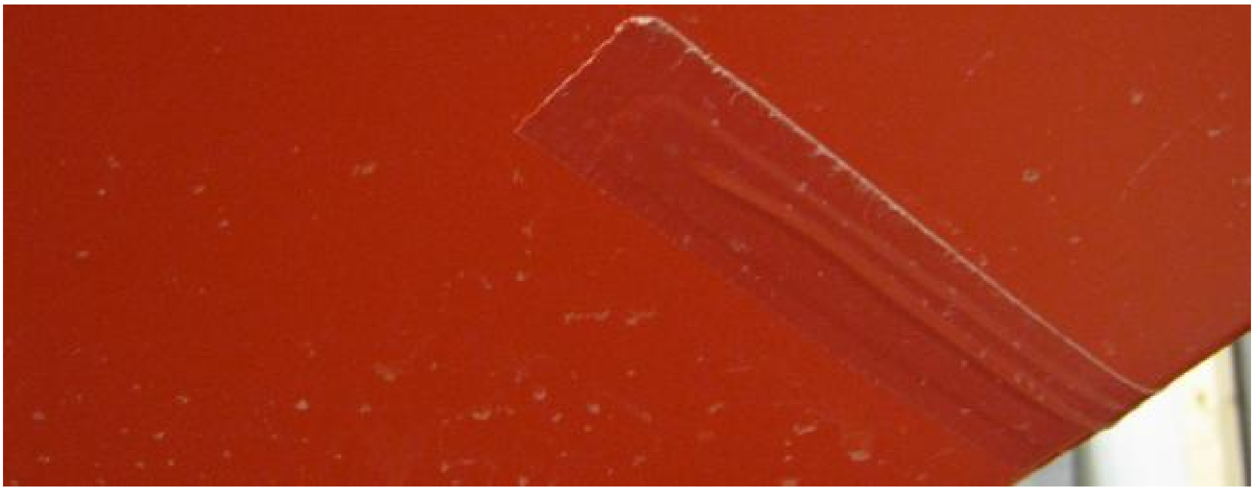


Figure 2-6: The turbulence stimulator was made from a welding wire which had two layers of tape above it. The first tape layer was half of the width of the second.

3. TEST PROCEDURES

3.1. Measurements

The following quantities were recorded as an analogue signal and digitally sampled on computer during the tests:

- Speed of the carriage
- Towing force

The open water resistance was measured in previous tests and it is presented in the Phase I report. All tests were towing tests without propulsion. The same arrangement was used in all tests.

In the beginning of the test series, all the force transducers were calibrated. The resistance and ice properties were measured according to the standards of AARC.
All tests were recorded on video. Videos were taken from the side of the test basin and underwater videos were taken through side and bottom windows of the basin. In addition, the bow of the model was filmed with a regular video camera and a high-speed video camera.

The flexural strength of the model ice was measured with a simple beam test and the elastic modulus of the ice was determined by measuring the deflection of the ice sheet when different weights were placed on the ice. After the test runs, the ice thickness was measured from the sides of the channel. The cracks which were formed onto the ice sheet were measured when the cracks were visible.

3.2. Calculations

The ice resistance R_I is determined in a following way. First, an average of the total resistance R_{IT} is calculated from an interval when the signal was constant. Then the open water resistance R_{OW} is subtracted from the total resistance in order to have the ice resistance (equation (1)). Finally the measured ice resistance is corrected with strength and thickness correction factors (equation (2)). The exponent X is 1.6 and it is based on previous model test data. The resistance is scaled to full-scale with equation (3).

$$R_{I,measured} = R_{IT,measured} - R_{OW} \tag{1}$$

$$R_I = \left(0.33 \cdot R_{I,measured} \cdot \left(\frac{\sigma_{f,target}}{\sigma_{f,measured}}\right) + 0.67 \cdot R_{I,measured}\right) \cdot \left(\frac{h_{i,target}}{h_{i,measured}}\right)^X \tag{2}$$

$$R_{I,ship} = \lambda^3 \cdot R_{I,model} \tag{3}$$

4. TESTDAY 30.9.2010

The previous tests performed in Phase I indicated that the model ice is not brittle enough as the model broke too big pieces and pushed the pieces aside instead of submerging them. The ice did not crush when in contact against the hull. Also the bow wave was too small compared to full-scale. This is probably because the ice sheet does not break in similar way as in full-scale and the big pieces restrict the wave-making.
The objective of this test was to test if production of more brittle model ice is possible and investigate its effect on ice resistance. The greatest problem in model ices used world-wide seems to be the low E/σ_f ratio and thus the insufficiently brittle behaviour of the model ice (Nortala-Hoikkanen 1990).

The FGX model ice, which is used at AARC, is made by spraying water above the tank water surface in freezing temperatures. The water drops freeze in the air into small ice crystals and the model ice layer is formed. Initial seeding has to be done before spraying in order to have an uniform bottom layer for the ice sheet.
The salinity of the spraying water is varied during the spraying process. It has been noticed that using fresh water spraying in bottom layers of the FGX model ice increases the stiffness of the ice sheet (Nortala-Hoikkanen 1990). In other words the fresh water layers increase the E/σ_f ratio.

For this test, more fresh water layers were sprayed during the ice manufacturing process. The objective was to test if the brittleness of the model ice could be increased by using more fresh water. The model was towed at 1.84 m/s (16 kn at f.sc.) and the results were compared to test done at same speed in regular model ice (Phase I).

4.1. Results and visual observations

The calculation of ice resistance along with ice properties and a full-scale prediction (column f.sc.) is presented in Table 4-1. The full-scale prediction is based on full-scale tests made in the Phase I. The ice resistance is calculated with equations (2) and (3).

Table 4-1: Calculation of the ice resistance. Speed 1.84 m/s = 16 kn in f.sc.

R_{IT}	R_{OW}	$R_{I,measured}$	$h_{i,measured}$	$\sigma_{f,measured}$	E/σ	$R_{I,model}$	$R_{I,ship}$	f.sc.
178.9 N	77.6 N	101.3 N	15.3 mm	29.4 kPa	5237	96.0 N	768 kN	372 kN

The ice resistance in regular ice was 95.9 N so the ice resistance in less saline ice is basically the same. The measured resistance is high compared to full scale data and calculation methods.

The ice properties were measured from two frames (longitudinal coordinates) of the basin. The flexural strength was measured from three spots on both frames. The flexural strength and elastic modulus varied quite much within the ice sheet. The difference between the average flexural strengths of the frames was 63 % and E/σ_f ratios of the frames were 1747 and 8727. Usually the E/σ_f ratio is little above 1000. It is clear that the properties of the ice sheet were not as controlled as normally. The values presented in Table 4-1 are from that part of the basin where the resistance was measured. E/σ_f ratio of the table is the average value.

Even though the E/σ_f ratio was rather high, the ice sheet deflected considerably according to visual observations. Similar circular cracks as in previous high speed tests were formed into the ice sheet but they were more difficult to detect and therefore measuring them turned out to be infeasible. The interval of the cracks is determined from high-speed video by calculating the average time between the cracks. The distance is approximately 42 cm which is nearly the same as the previous measured values in the Phase I (36 & 39 cm).

The underwater footage was similar than in previous tests at same speed (Figure 4-1).

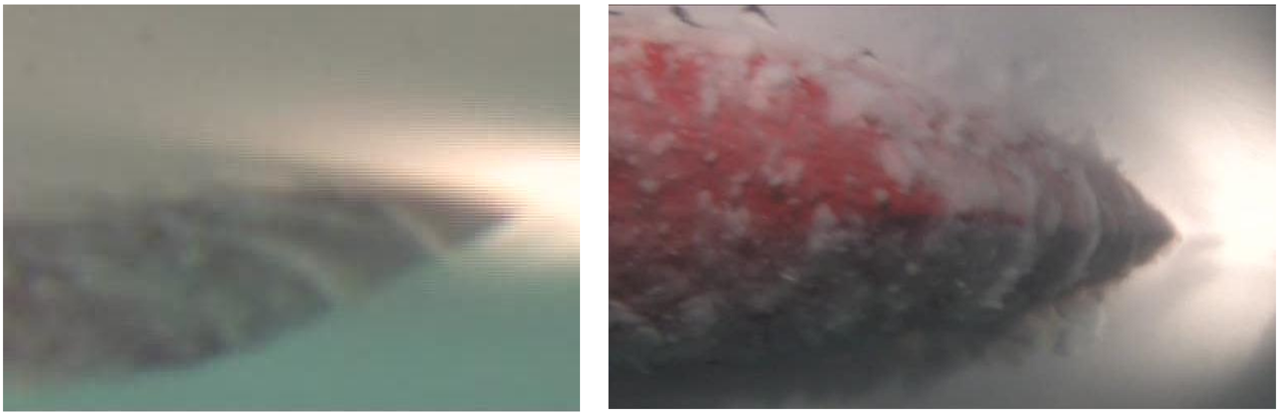


Figure 4-1: Similar layer of slow moving ice with waves of crushed ice as in previous tests was visible in underwater footage.

The video-footage taken with the high-speed camera revealed some differences between the breaking process in less saline ice and in regular. In Figure 4-2 it can be seen that the less saline ice breaks/crushes into smaller pieces when in contact with the hull. However, the model still seems to break into too big pieces when compared to full-scale (Figure 4-3).

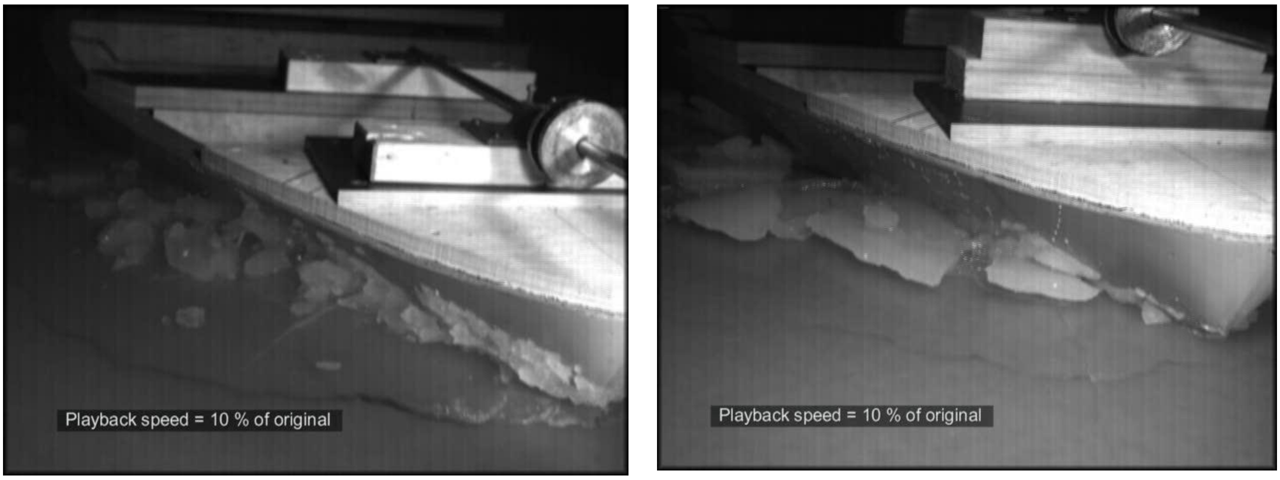


Figure 4-2: Breaking the ice at 1.84 m/s. Left = less saline ice; right = normal model ice.

Figure 4-3: Ice breaking in full scale at high speed.

4.2. Conclusions

The less saline ice gave basically the same results as the regular ice and the ice did not seem to be more brittle. However, the high-speed video revealed some promising results as the ice was crushed into smaller pieces when in contact with the hull.

Production of more brittle model ice is a difficult process and would need a thorough research on model ice properties. Simply adding more fresh water does not make the ice more brittle and resulted some peculiar behaviour of the ice as the ice properties varied relatively much within the ice sheet. Therefore it would also be necessary to produce several calibration ice sheets and thorough research on how to control the properties of the model ice sheet.

Due to the complicated problems relating to the model ice properties which would need a totally own research as the brittleness is problem on all model ices, the next model tests were decided to focus on the underwater phenomena.

5. TESTDAY 1.10.2010

The measured ice resistance in model test performed at Aalto University started to deviate considerably from the calculated values (the Lindqvist prediction) at 6 knots and higher speeds. As it was not possible to have underwater footage in the tests performed at Aalto University and the high speed tests performed at AARC revealed some peculiar ice movement under the hull, it was decided to perform the tests at 6 knots and 12 knots speed also at AARC. The objective was to study if the ice resistance at AARC deviates from the calculation methods in a similar manner like at Aalto University and also to obtain underwater footage at lower speeds.

The model was towed and stopped between the test runs. The speed of 0.69 m/s (6 kn in f.sc.) was performed in the first part of the basin and 1.38 m/s (12 kn in f.sc.) in the latter part of the basin.

5.1. Results and visual observations

The calculation of ice resistance along with ice properties and a full-scale prediction (column f.sc.) is presented in Table 5-1 and Table 5-2. The full-scale prediction is based on full-scale tests made in the Phase I. The ice resistance is calculated with equations (2) and (3).

Table 5-1: Calculation of the ice resistance. Speed 0.69 m/s = 6 kn in f.sc.

R_{IT}	R_{OW}	$R_{I,measured}$	$h_{i,measured}$	$\sigma_{f,measured}$	E/σ	R_I	$R_{I,ship}$	f.sc.
57.1 N	11.7 N	45.5 N	15.3 mm	32.6 kPa	1229	41.9 N	335 kN	174 kN

Table 5-2: Calculation of the ice resistance. Speed 1.38 m/s = 12 kn in f.sc.

R_{IT}	R_{OW}	$R_{I,measured}$	$h_{i,measured}$	$\sigma_{f,measured}$	E/σ	R_I	$R_{I,ship}$	f.sc.
155.8 N	40.3 N	115.5 N	15.9 mm	28.7 kPa	1229	104.1 N	832 kN	293 kN

The measured ice resistances at AARC (Phase I & II) and at Aalto University (Phase I) along with the obtained full-scale results (Phase I) are presented in Figure 5-1. It can be seen that model tests also at AARC give unrealistically high ice resistance predictions. The resistances starts to deviate considerably after 6 knots speed and the resistance is at its highest at 12 knots speed. At 16 knots speed the resistance is already lower than at 12 knots as the resistance starts to drop around 13 knots.
The measured ice resistance is smaller at AARC. It should be taken into consideration that the open water resistance at Aalto university is determined with a turbulence stimulator (a common procedure at Aalto) while at AARC the turbulence stimulator was not used. This slightly increases the difference between AARC and Aalto but not considerably.

Underwater footage (Figure 5-2 & Figure 5-3) reveals that the bow is considerably covered in ice at 12 knots speed. The ice layer is bigger than at 16 knots speed. This could explain the reduction of the ice resistance at the highest speeds as there seems to be less ice sticking the bow. Similar waves of crushed ice (although a little smaller) as in previous high speed tests are visible also at 12 knots speed. At 6 knots speed the ice breaking process looks more normal.

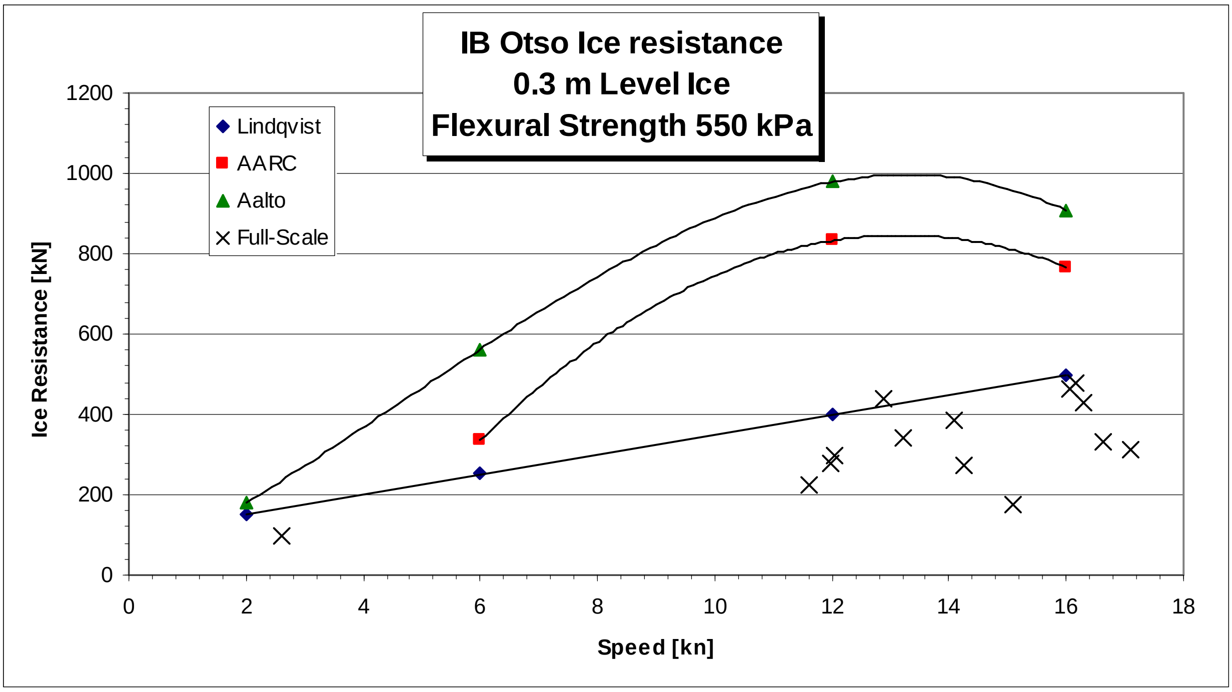


Figure 5-1: The measured ice resistance for IB Otso.

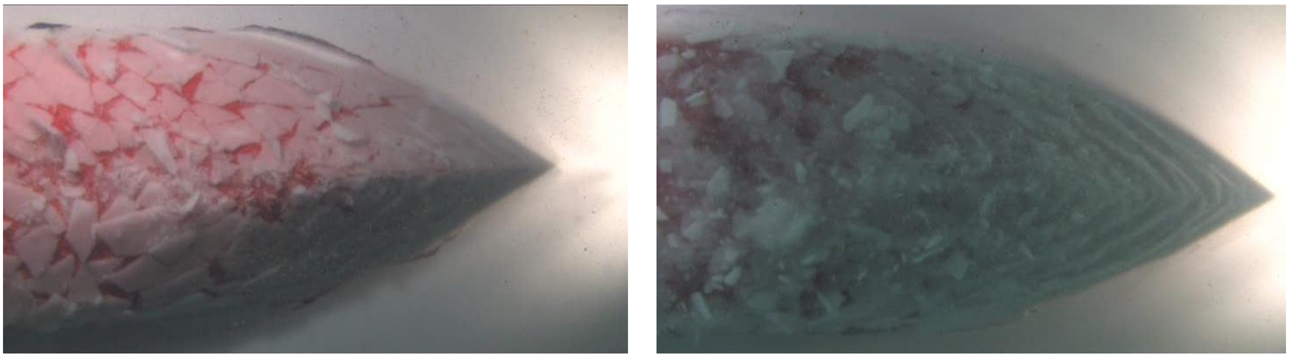


Figure 5-2: Underwater footage. Left = 0.69 m/s (6 kn); right = 1.38 m/s (12 kn). The bow is considerably covered in ice at 1.38 m/s speed.

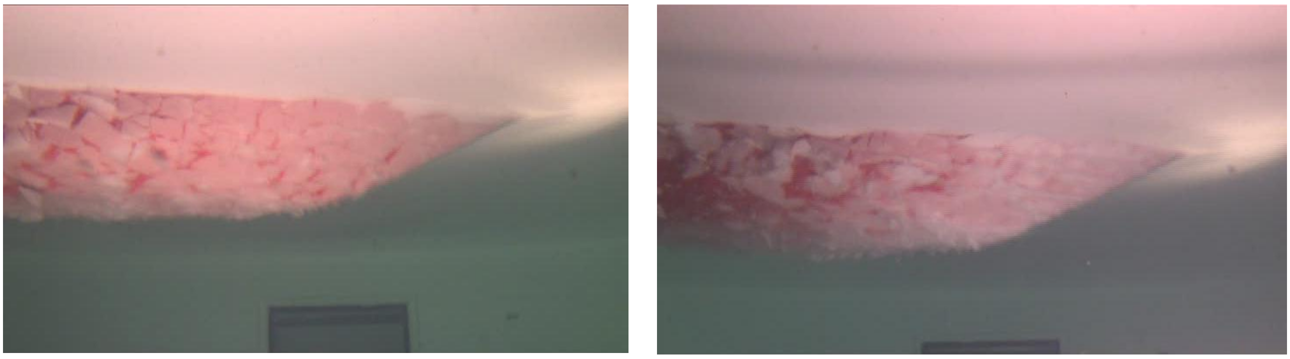


Figure 5-3: Underwater footage. Left = 0.69 m/s; right = 1.38 m/s. Small waves of crushed ice can be seen above the ice layer in the right picture.

5.2. Conclusions

Tests performed at 6 knots and 12 knots speed demonstrated that the ice resistance starts to increase after 6 knots speed also at AARC although the difference is not as big as at Aalto University. The highest resistance is at 12 knots speed. At the same time it is visible that the ice pieces are sticking against the bow more and more when the speed increases (Figure 5-2 and Figure 5-3). The resistance is highest at 12 knots speed and also the ice coverage on the bow is greatest at 12 knots speed. Therefore it seems that the increase of ice resistance originates mainly from the slow moving ice layer against the bow. It is possible that the ice breaking process itself is somehow related to the slow moving ice layer as the measured ice resistance in pre-sawn ice (Phase I) is of a correct magnitude.

As the measured ice resistance in full-scale is not increasing as steeply with speed as in model-scale, it is possible that the ice pieces stick against the bow only in model-scale. Obtaining underwater footage at high speeds in full-scale is somewhat impossible.

6. TESTDAY 15.12.2010

The previous ice model tests indicated that the ice pieces sticking against the bow are possibly the biggest contributor to the high ice resistance. Kämäräinen (2007) has studied a pressure decrease between the ship hull and a ice floe when the ice is submerged. This low-pressure phenomena can result a friction force which is several times the force resulting from the static lift of the ice floes. According to Kämäräinen the pressure drop may be caused by inertia forces or by changes in the hull geometry. Literature has also presented a third phenomena which could result the pressure drop: ventilation.

Low pressure between the hull and ice floes could explain why the ice pieces are sticking against bow of the model. It is unlikely that ventilation would result the low pressure as the ice is more crushed at high speeds than bent down in big pieces. It is more likely that the acceleration of water in the gap between the hull and ice floes results the pressure drops.

In this model test it was tried to disturb the flow between the hull and ice floes. A turbulence stimulator was installed on the bow of the model (presented in chapter 2). Due to the low Reynold's number the viscous forces are magnified in model scale. The turbulence stimulator could disturb the flow and reduce the resistance. In addition, as the flow is turbulent, the pressure difference between the gap and below the ice floes could even as the ice pieces do not form such a uniform layer against the bow.

As the ice resistance is at its highest at 12 knots speed, the test was performed at corresponding speed (1.38 m/s). The model was towed.

6.1. Results and visual observations

The calculation of ice resistance along with ice properties and a full-scale prediction (column f.sc.) is presented in Table 6-1. The full-scale prediction is based on full-scale tests made in the Phase I. The ice resistance is calculated with equations (2) and (3). The same open-water resistance as without the turbulence stimulator is used.

Table 6-1: Calculation of the ice resistance. Speed 1.38 m/s = 12 kn in f.sc.

R_{IT}	R_{OW}	$R_{I,measured}$	$h_{i,measured}$	$\sigma_{f,measured}$	E/σ	R_I	$R_{I,ship}$	f.sc.
154.3 N	40.3 N	114.0 N	15.7 mm	21.7 kPa	1078	115.4 N	923 kN	293 kN

The ice resistance of the model without turbulence stimulator was 104.1 N so the turbulence stimulator increased the resistance approximately by 11%.

Underwater footage of the tests is presented in Figure 6-1, Figure 6-2 and Figure 6-3. It can be seen that the piece size is reduced with turbulence stimulator. It is likely that the ice pieces hit the stimulator even though the dimensions of the stimulator were chosen to be relatively small. There is still a ice layer against the bow but it does not look as accumulated as with the original hull without the turbulence stimulator. Small waves of crushed ice above the ice layer are visible in the side view.

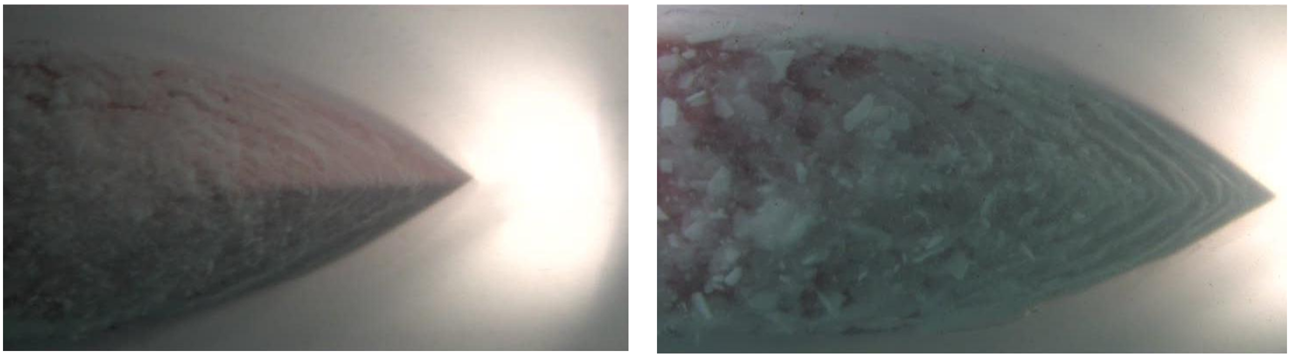


Figure 6-1: Underwater footage. Left =turbulence stimulator; right = original hull.

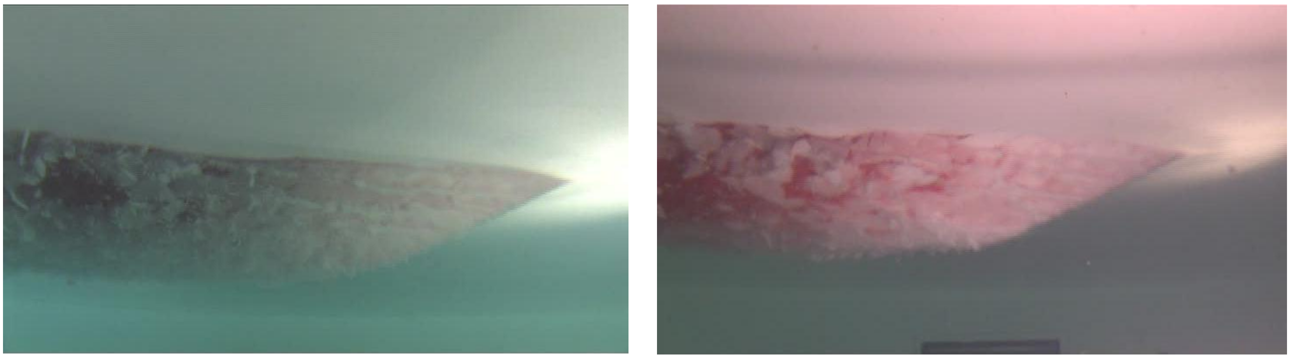


Figure 6-2: Underwater footage. Left =turbulence stimulator; right = original hull.

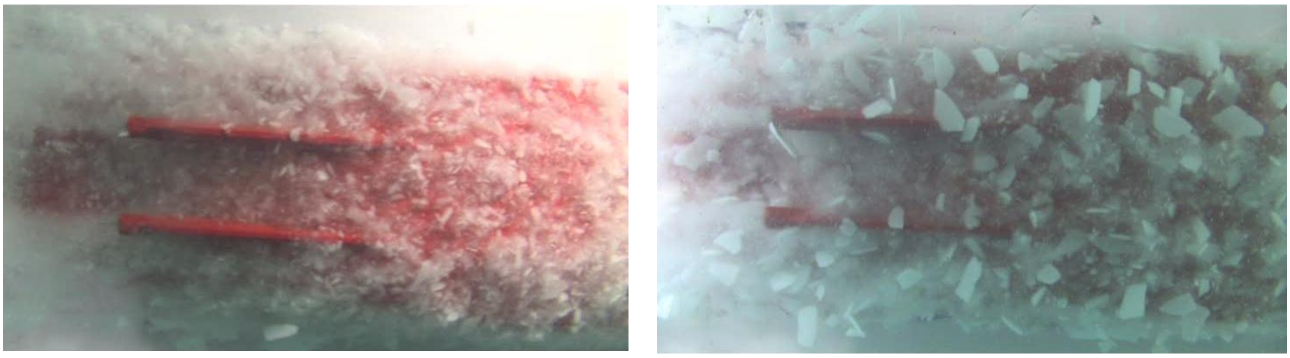


Figure 6-3: Underwater footage. Left =turbulence stimulator; right = original hull.

6.2. Conclusions

The turbulence stimulator did not function as desired. It increased the ice resistance instead of reducing it. An additional resistance arises as the ice pieces hit the stimulator. There is still a slow moving ice layer against the bow, although it does not look as bad as without the turbulence stimulator. Without the stimulator the ice seems to be pressing more and accumulating on the bow.

The test with turbulence stimulator indicated that either the slow moving ice layer is not formed because of low pressure between the ice floes and the hull or the turbulence stimulator was not able to disturb the flow and even the pressure differences.

7. TESTDAY 22.12.2010

For the final test of the whole test series, model ice properties were varied again. Harder model ice was produced (referred as tough ice from now on) as the flexural strength of the ice was approximately twice the target strength. The strength was scaled down to the same value (27.5 kPa) as in previous tests with the strength correction factor.

The purpose of the test was to study the strength dependence and the importance of the flexural strength of the ice resistance. As the previous tests indicated that the model ice is not brittle enough. Freezing the ice for a longer period will make it more brittle but also increase the flexural strength which is later scaled down.
The compressive strength of model ice does not model correctly as it is relatively too small due to the homogenous crystal structure (Nortala-Hoikkanen 1990). It is possible that the normal model ice is too soft in horizontal direction and as the speed of the model increases and the ice pieces hit each other, the ice compressed and crushed together and ice pieces stick against the bow. As the ice is harder, less compression occurs and the ice probably slides better along the hull surface. The compressive strength of the model ice was not tested as there is no widespread and reliable method for testing the compressive strength of model ice.

Once again the model was towed. The speed was 1.38 m/s (12 kn in f.sc.) as the resistance is at its highest then. The turbulence stimulator from the previous test was still intact and the results were compared.

7.1. *Results and visual observations*

The calculation of ice resistance along with ice properties and a full-scale prediction (column f.sc.) is presented in Table 7-1. The full-scale prediction is based on full-scale tests made in the Phase I. The ice resistance is calculated with equations (2) and (3). The open-water resistance without the turbulence stimulator is used. The flexural strength is scaled down to $\sigma_{f,target}$ = 27.5 kPa (550 kPa in f.sc.) with the strength correction factor.

Table 7-1: Calculation of the ice resistance. Speed 1.38 m/s = 12 kn in f.sc.

R_{IT}	R_{OW}	$R_{I,measured}$	$h_{i,measured}$	$\sigma_{f,measured}$	E/σ	R_I	$R_{I,ship}$	f.sc.
167.4 N	40.3 N	127.1 N	17.9 mm	44.8 kPa	1683	83.8 N	670 kN	293 kN

The measured ice resistance in tough ice is lower than in normal ice, approximately 27.5 %. It is interesting to notice that the ice resistance in tough ice is lower than in normal ice even without the strength correction (~96 N). However, the ice resistance is still high when compared to full-scale data and empirical calculation methods as can be seen in Figure 7-1.
The results from normal and tough model ice are not directly comparable as such a big difference in flexural strength also affects the piece size. The breaking patterns in normal ice and in tough ice are presented in Figure 7-2. It can be seen that the piece size is bigger when the flexural strength is higher.

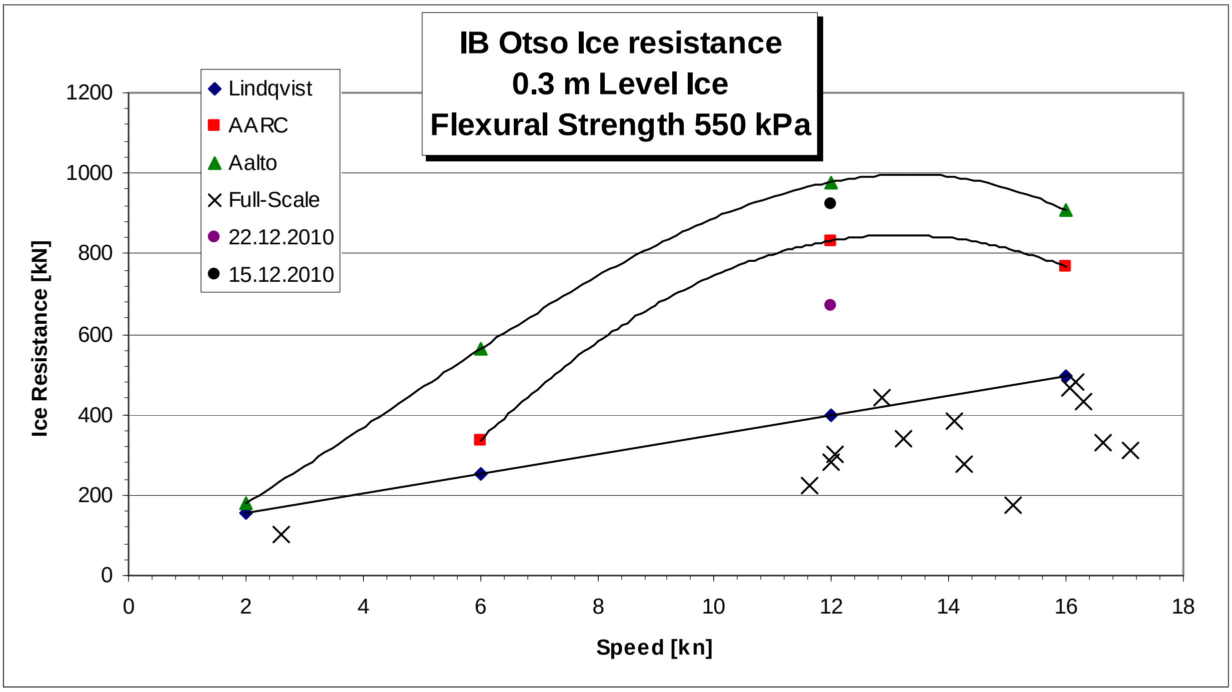


Figure 7-1: The measured ice resistances of all tests. A turbulence stimulator is used at 15.12.2010 and 22.10.2010.

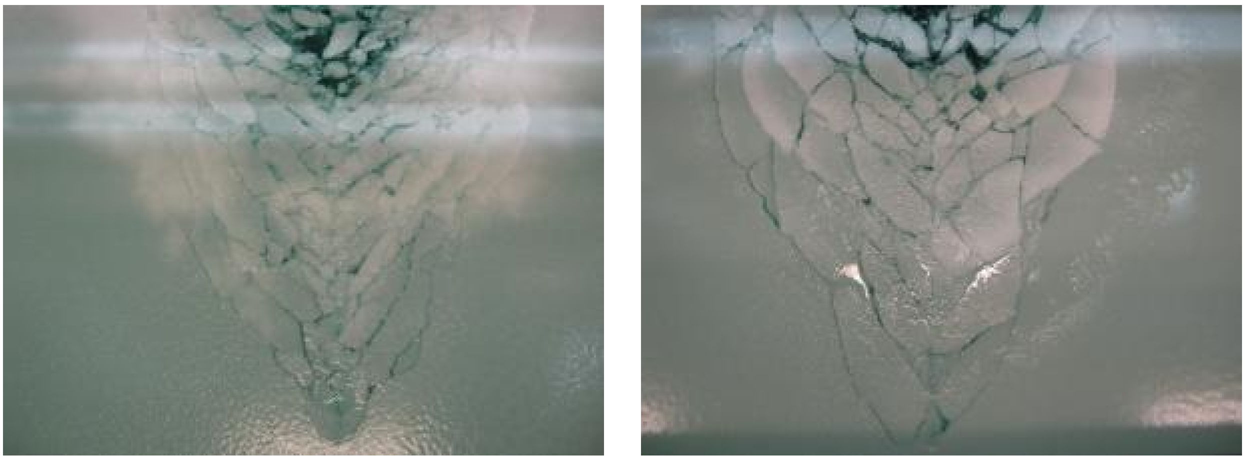


Figure 7-2: The breaking patterns. Left = 15.12.2010; right = 22.12.2010.

The bigger piece size is also visible in underwater footage (Figure 7-3 & Figure 7-4). Crushing is happening at stem more than on other tests according the video material. There is still a slow moving ice layer against the bow but the layer does not look as accumulated as in the test done at the same speed in regular ice without the turbulence stimulator.

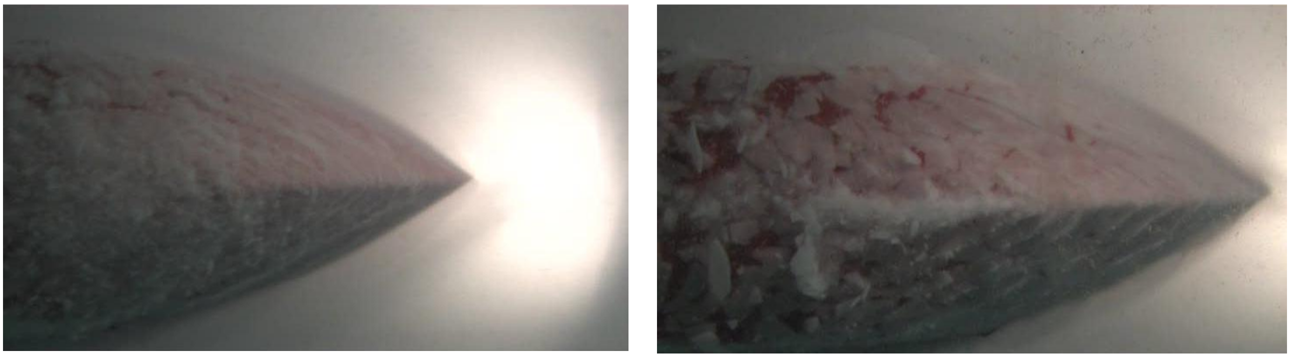


Figure 7-3: Underwater footage. Left = 15.12.2010; right = 22.12.2010.

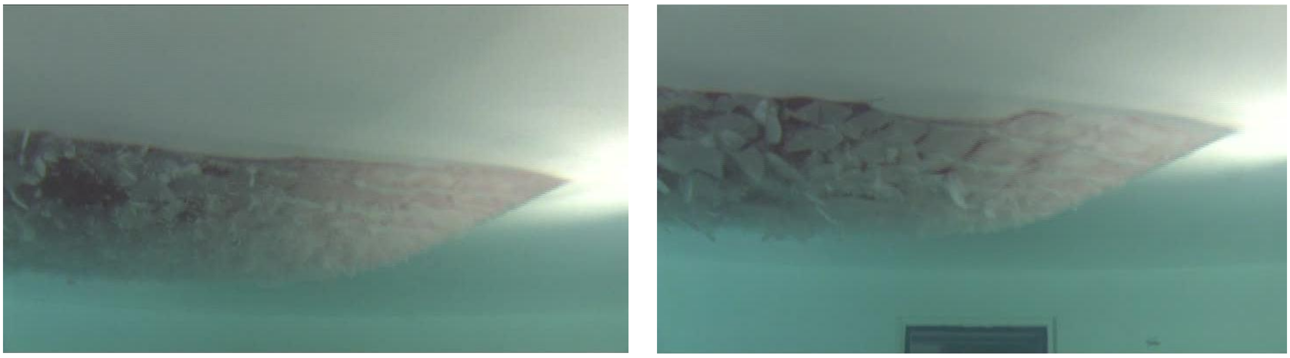


Figure 7-4: Underwater footage. Left = 15.12.2010; right = 22.12.2010.

7.2. Conclusions

The ice resistance was clearly reduced as the flexural strength of the ice was increased. The resistance is lower even without the strength correction. It is not totally clear why the resistance dropped. The slow moving ice layer against the bow seems to be still present. The piece-size is clearly larger than in previous tests. Seems that bending of the ice is not as dominant as at lower speeds. Further research is needed to understand the reason why the resistance reduced.

8. CONCLUSIONS & DISCUSSION

There is a growing need to increase the escort speeds in ice and at the same time the effects of speed on the icebreaking process are poorly known. In addition there has been some indications that model tests are unreliable at speeds above 10 knots. The purpose of this study was to gain more information about the ice breaking process at higher speeds.

This study started as an investigation on the effect of speed on the ice resistance of a ship. The effects of speed were studied experimentally by performing model tests in ice. **During the project it was found out that model tests do not work well at higher speeds (at least with relatively thin ice sheets which were used in this study) as they give unrealistically high ice resistance predictions.** The focus of the study shifted from full-scale to model-scale as the phenomena resulting the high resistance was tried to discover.

Visual observations were crucial and they indicated that the high resistance most likely originates from submerged ice pieces sticking against the bow of the model and forming a slow moving ice layer against the bow. Also the model ice properties seem to affect the resistance as the model ice is not brittle enough. These two phenomena seem to be somehow linked together as the resistance in presawn ice (when presumably no breaking occurs) is of right magnitude. It is unlikely that a similar layer of ice against the bow is present in full-scale as the measured full-scale data does not indicate such a steep increase of ice resistance with speed.

The phenomena which results the slow moving ice layer against the bow was not solved in this study. Understanding and researching the phenomena and the theory behind it is crucial in the future if model tests at speeds above 10 knots are to be performed. The reason why the slow moving layer exists should be resolved, as well as how does it affect the resistance and is there a similar layer in full-scale.
Pressure field below ice pieces have not been thoroughly studied and needs more research. It is possible that the pressure field around the hull is completely different in ice than in open-water. Maybe the reduced wave making results a high pressure on the front of the bow which presses the ice pieces against the hull. And maybe this pressure is still magnified as the model ice does not behave like natural ice.

More brittle model ice should be developed in future. Currently the model ice does not behave realistically at higher speeds. However, development of more brittle model ice is an extremely difficult task as problems of model ice are acknowledged since the early days of model ice production and still no ideal model ice has been developed.
Also more research on the compressive strength of model ice is needed. Crushing and compression of the ice seems to become more important as the speed of the vessel increases.
In addition, more investigation on other model ice properties could be beneficial. The desired flexural strength for model ice is obtained by freezing the ice until it has a correct frostsum (C°h). The same frostsum can be obtained by freezing the ice with a low temperature for a short period of time or by freezing the ice with a little higher temperature for a little longer time. This will affect how uniformly the model ice is frozen in vertical direction although the flexural strength is the same. There is no research on how does different freezing temperatures affect the compression strength and brittleness of the model ice. The amount of cold can also affect the

smoothness of the model ice surface which in turn affects the friction coefficient between the model and ice.
When comparing natural and model ice, it should be taken also into consideration that the model ice is rather ideal and homogenous material. Natural ice has always some imperfections in it. Maybe this could be one reason explaining different behaviour between natural and model ice.

This study revealed which are the main problems on model tests at high speeds. Subjects for future research are presented above. These problems should be resolved in order to have more accurate model test predictions at higher speeds. It would be feasible to focus first on the problems relating to the slow moving ice layer against the bow and later focus more on model ice properties when the physical phenomena relating to ice breaking process are more clear.

REFERENCES:

Heinonen, Teemu. 2010
An experimental study on the effect of speed on the ice resistance of a ship, Phase I
AARC Report A-443

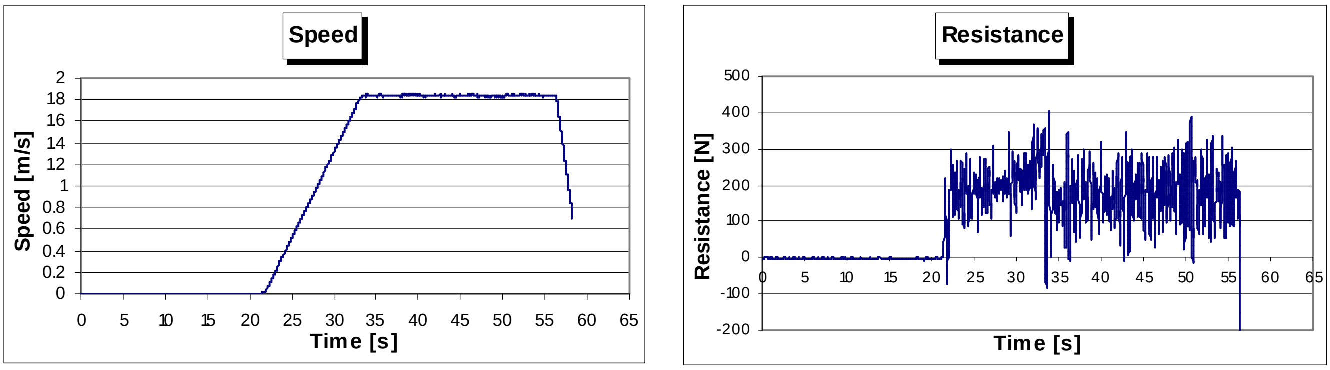
Kämäräinen, Jorma. 2007
Theoretical investigation on the effect of fluid flow between the hull of a ship and ice floes on ice resistance in level ice.
Doctoral Dissertation. Helsinki University of Technology. Department of Mechanical Engineering. TKK Dissertations 80.

Manderbacka, Teemu & von Boch und Polach, Rüdiger & Heinonen, Teemu. 2010.
Ice Breaker Otso-model ice resistance measurements, their comparison to previous results and a study of the surface roughness effect to the ice friction.
Aalto University. School of Science and Technology. Report AALTO-AM-20

Nortala-Hoikkala, Anita. 1990
FGX model ice at the Masa-Yards Arctic Research Centre
IAHR ice symposium 1990, vol. 3. pages 247-259

APPENDIX A TIME HISTORIES, PHASE II

List of figures:



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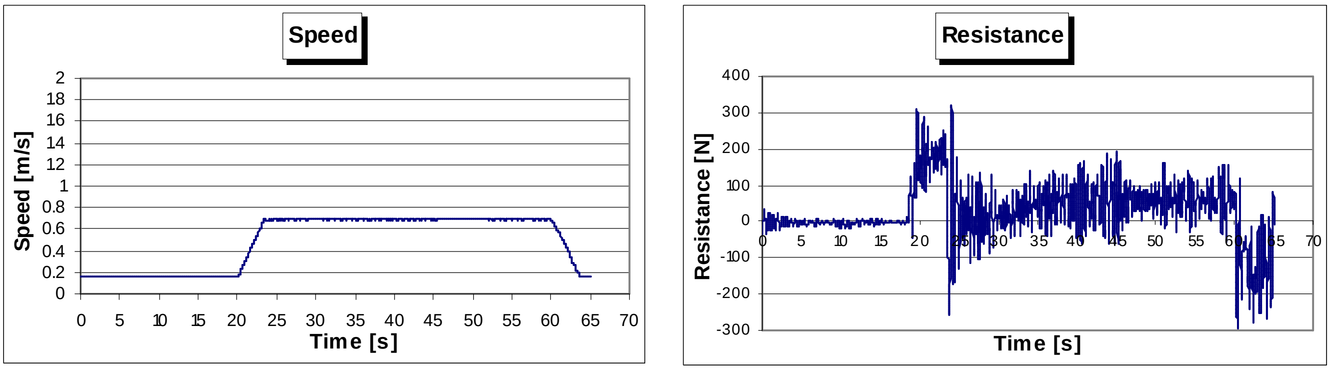

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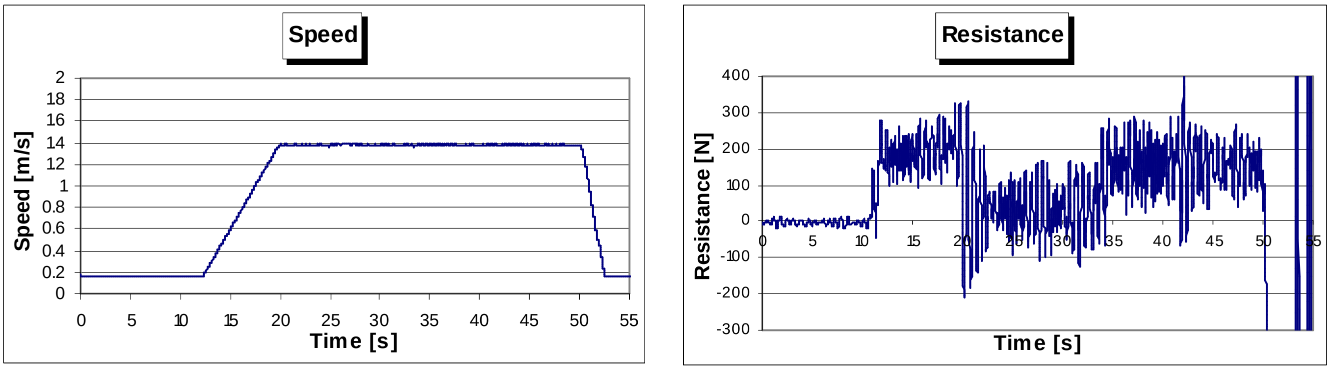

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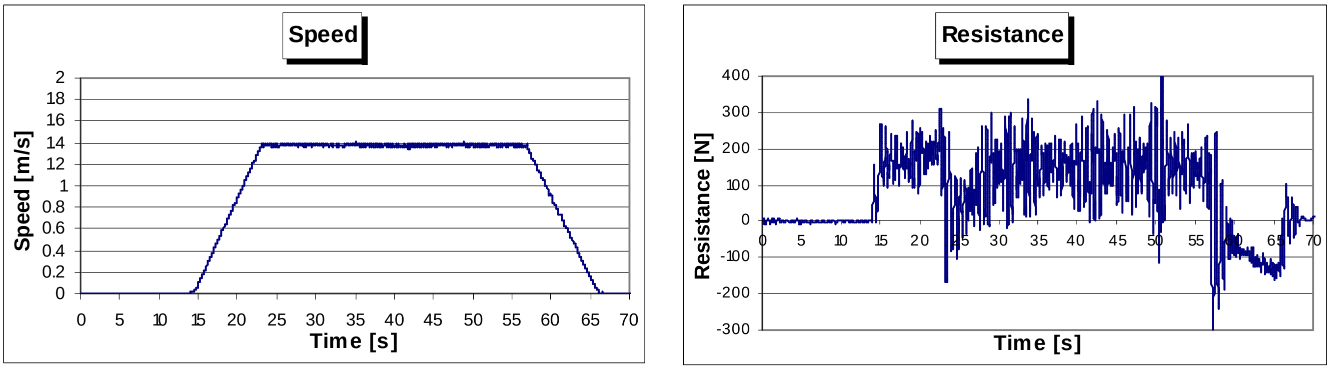

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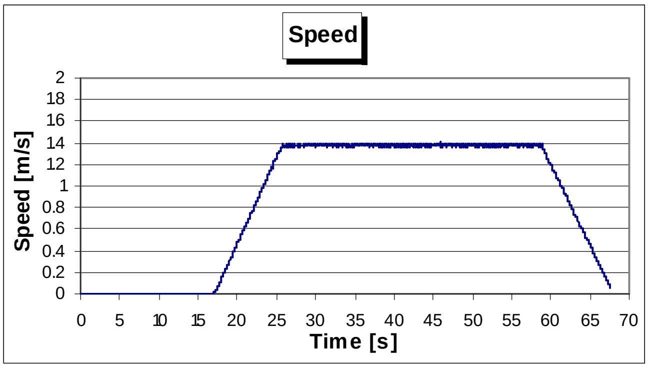

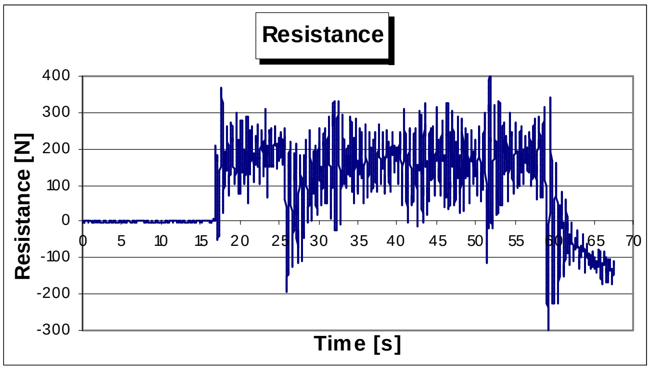

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