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Model test method development for reviewing notch towing properties of an icebreaker

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ABSTRACT

Notch towing is one of the most important assistance methods for icebreakers in the Baltic Sea. The aim of this paper is to introduce a study in which a model scale test method for reviewing towing properties of an icebreaker was developed. The study included a short literature study and an experimental part where notch towing operations were tested in model scale.

The literature study describes the theory of notch towing in terms of the most significant factors such as resistance and turning characteristics. Also, the applicable model test procedures such as manoeuvring tests on a single ship in ice and other literature related to model tests and model ice are presented. This is followed by an introduction to a full-scale notch towing study, which is later used to review the towing force magnitude in the model tests conducted in this study.

Next the research method and plan for the experimental part are presented, as well as the ship models used in the experiments. The experiments included five individual model tests in which 90-degree manoeuvring tests were performed using self-propulsion of the icebreaker to tow the assisted ship. The models used in the experiments were icebreaker Polaris and a typical merchant ship suitable for winter navigation in the Baltic Sea.

The main result of the study is proving the functionality of performing a 90-degree turn when modelling the notch towing situation. Other important results are the towing force, the speed of the models and the change of heading of the models as a function of time. In addition to this, the turning diameter is an important result. The measurements show that the scaled towing force settles between 35 and 55 tons at a speed of about two knots. The measured turning diameters range from 400 to 4300 meters.

KEY WORDS: Icebreaker; Notch towing; Model test; Manoeuvring.

INTRODUCTION

Approximately 90 percent of Finnish export is transported by ships. Freezing of sea regions like northern parts of the Baltic Sea creates unique challenges for shipping.

When navigating in frozen waters ships need the help from icebreakers. Icebreakers assist merchant ships typically by five different ways (Rosenblad, 2007). These ways are (1) breaking loose, (2) escorting, (3) convoy, (4) convoy with two icebreakers and (5) towing. Icebreaker can also tow a ship while leading a convoy. It is believed that merchant ships will need icebreaker towing to an increasing extent in the future because of decreasing engine powers due to EEDI regulations. (Westerberg, 2014; Heinonen, 2017)

Design process of an icebreaker includes usually model scale tests in ice, which can give a comprehensive understanding of ice-going capability in different ice conditions. The tests can also include towing tests, but those normally focus on situation where the ships are driven straight.

The International Towing Tank Conference (ITTC) has given recommended procedures and guidelines for model tests in ice for a single ship. Literature for manoeuvring while towing is very limited. This paper aims to introduce a study in which a new method to investigate the notch towing properties of an icebreaker is developed through applying existing procedures on model scale testing in ice to a new situation. To review the method, a full-scale towing study is used when comparing towing forces.

At first, the study evaluates what features make an icebreaker good in a towing situation by the phenomena of notch towing in theory and describes the parameters affecting towing properties. After that a model test method and series are engineered and performed. Finally, based on theoretical knowledge and measurement results the functionality of the developed method is evaluated.

Research questions are as follows:

1. Which parameters affect assistance properties of an icebreaker?

2. What kind of model test method can best be used to review the towing properties of an icebreaker?

More specifying questions are as follows:

3. How should the model tests be performed in terms of test methods and measurements?

4. Which factors are the most significant in terms of modelling the towing situation and how should they be considered?

5. How well does the model test method developed correspond to the phenomena in full-scale?

6. How much influence does the bow propulsion of the icebreaker have on turning of the towing combination?

Because there are working methods to study towing while going straight, this study focuses on considering a notch towing situation. In this study, turning tests were performed with two ships. When a Baltic icebreaker is towing a merchant ship, the towed ship is attached to the aft of the icebreaker with wires. The icebreakers aft include a shape for the towed ship’s bow to limit lateral movement of the towed ship’s bow. This shape is called a towing notch, which is where the term notch towing comes from.

Towing operations are believed to become more and more common due to emission restrictions. Icebreaker towing has direct impact on the functionality of the winter navigation system. When icebreakers towing capability is good the whole winter navigation system is more efficient, and this has a direct impact on economy.

While towing model tests have been focusing on a situation where towing combination is driven straight, there is a clear deficiency in model test procedures. In Baltic Sea the manoeuvrability is in key role regarding towing operations. This paper introduces a new method for reviewing situation which has not been studied earlier in model scale.

A ship is always a compromise, and the operating characteristics are chosen according to the intended use already in the design phase. If towing properties of an icebreaker can be examined in model scale, this gives a great advantage for design.

NOTCH TOWING IN THEORY

One essential assistance method for icebreaker is towing. Towing is needed when ice conditions are so harsh that the assisted ship gets stuck or can't follow icebreaker with desired speed (Heinonen, 2017). Notch towing is the most common and effective towing method that Baltic icebreakers utilize (TraFi, 2011).

Notch towing is started by reversing the icebreaker's towing notch against the assisted ship's bow. Towing cable of the icebreaker is then attached to towed ship's bow bollards. After that the cable is tightened so that the towed ship's bow doesn't slip from the towing notch. Every ship's bow doesn't fit to towing notch. If so, a gap needs to be left between the ships. In this kind of situation there is a risk of collision if the icebreaker's speed suddenly drops.

During towing operation, the icebreaker has the biggest impact on speed and course changes. The assisted ship acts kind of a large rudder strongly resisting turning (TraFi, 2011).

Resistance

Towing operations are affected by several factors. The speed of the towing combination is always affected by total thrust and total resistance of the ships, see Figure 1. The total resistance is a sum of ice resistance, open water resistance and air resistance.

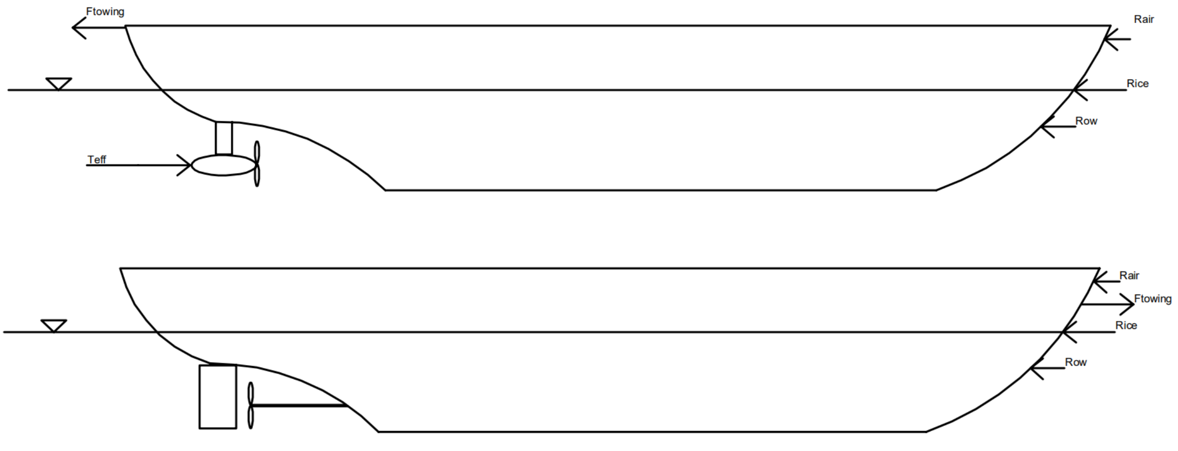

Figure 1. Resistances, towing force and thrust acting on the icebreaker (above) and the assisted ship (below) during towing.

There are several ways to define level ice resistance of a ship. Lindqvist (1989) has developed a simplified way to define level ice resistance, which is based on three resistance components. These components are crushing, bending, and submersion. The effect of speed and friction are also considered. Icebreakers ice resistance can be estimated with this method in towing operation. The towed ship however advances in the icebreaker's channel, not in level ice. The earlier mentioned method can be used to estimate towed ship's resistance by assuming crushing and bending as zero.

Towed ship's resistance can also be estimated with ice channel resistance calculating methods. Finnish-Swedish ice class rules implement Wilhelmson's (1996) method, in which calculations are based on soil mechanics and the internal friction of the loose ice mass. The most significant factor in this method is the thickness of loose ice mass in the channel. Functionality of the calculating method was validated with model tests.

Channel width effect on resistance

If icebreaker breaks channel that is narrower than the assisted ship, increases resistance of the assisted ship because she must also break level ice in the sides. Width of the channel broken by the icebreaker depends on icebreakers beam. Icebreaker with azimuth thrusters can widen the channel with propulsion utilizing toe-in angles (Gong & Matala, 2022). If the icebreaker is widening channel with propulsion, the loose ice mass in the channel will also move towards sides of the channel and out of the channel and the channel gets of higher quality in terms of merchant ship trafficability.

The ice channel is of the highest quality when it is clean of loose ice mass and is wider than the assisted ship. In such situation the assisted ship advances in principle in open water. However, no matter how high-quality the broken channel is, weather conditions can still create challenges for icebreaker operations as wind and current moves sea ice.

Turning during towing operations

In addition to resistance, another key factor in towing operations is icebreaker's turning ability. Turning ability is affected by forces resisting motion and forces turning the ship. Turning ability in open water is affected by e.g., hull shape, rudder area (conventional shaftline icebreaker), propulsion power and its direction. Turning force can be applied by turning propeller flow with rudder or turning azimuthing thruster. Naturally the position where the force acts affect how large is the resultant. The closer towards transom the force is applied, the greater the moment is. This is because the pivot point settles towards bow from centre of gravity when a ship is advancing ahead. Pivot point is the apparent centre of rotation, the point on a ship that follows circular path during turning circle manoeuvre. Its location is influenced by the hull shape, speed, acceleration, turning force location etc. Forces resisting motion are greater when navigating in ice which makes turning more difficult. It is noticed that the pivot point location isn't the same in towing situation when comparing to the icebreaker advancing alone.

Ko et al. (2017) studied turning characteristics of icebreaking vessels in level ice with numerical methods and with model tests. To understand which parameters affect turning characteristics they studied effect of length-beam ratio, rudder area, stem angle and shoulder angle on ship design parameters with numerical simulations.

Main results of the study were that length-beam ratio was found to have a large effect on turning characteristics in both open water and in ice. The longer and narrower the ship, the worse the turning characteristics are. Block coefficient, on the other hand had no major effect on the turning ability in ice. Regarding rudder area, it was stated that larger area improves turning ability. Variation of the shoulder angle on waterline was found to be much more related to the turning ability compared to stem angle.

Notch towing studies in model scale

For model tests on single ship there is accurate instructions available both for tests in open water and in ice. Instructions for model testing in ice includes ice measurements, performance tests and manoeuvring tests. For towing tests there are no instructions available but manoeuvring procedures for single ship can be applied for the situation.

ITTC (2021) model test procedures include turning circle trial, which is applied for towing situation in this study. Purpose of the self-propulsion test is to test how large area a ship needs for turning. The test can be conducted as a 360-degree turn or smaller if basin dimensions restrict turning. For this study 90-degree turn was selected to maximize usage of the ice field.

ITTC (2021b) states that effect of the scale on manoeuvring isn't yet fully understood. The inaccuracy from scale could be minimized by enlarging the size of the model if it is possible. In case of this study, it wasn't possible because the ship models were already existing. On the other hand larger models wouldn't be able to turn in the test basin.

Model ice properties create some uncertainty for towing tests. Matala (2012) states that compressive strength of sea ice is almost ten times larger compared to flexural strength. With model ice compressive strength although is approximately three times larger compared to flexural strength. Inadequate compressive strength of model ice is not a disadvantage in situation where icebreaking happens by bending. If a lot of crushing happens, the uncertainty increases. Crushing might happen at towed ship's side during tight turns.

Notch towing studies in full-scale

Heinonen (2017) collected towing force data in his full-scale study and interpreted the magnitudes. Aim was to also collect information about how merchant ships are typically applying for towing.

The measurements were conducted in the Bay of Bothnia and included 21 towing situations where towed ships were IA ice class merchant ships. The measurements showed that towing speeds were high, almost 10 knots in average. Measured average towing force was 36.8 tons and the highest measured towing force peak was 241 tons.

Large peaks in towing force seem to be induced mainly by two separate situations. First situation was momentary loosening of towing cable because of resistance increase in a difficult ice condition, which later resulted in rapid tightening of the towing cable. Another incident inducing high peaks in towing force was lateral movement of the towed ship's bow.

RESEARCH METHOD

The research method used in this study is model scale testing. Ship model scale testing was first used in 1860s, when William Froude created a method for predicting full-scale behavior based on results of open water model tests (Suominen, 2020). Since then, model test methods have become an integral part of a shipbuilding process. Model tests are done in both open water and in ice.

Testing method

In the literature section, a model test method for turning circle in level ice with single ship was introduced. In this study the turning circle procedure is applied to review notch towing situation. Test plan and used input parameters for model tests are introduced in

Table 1 below.

Table 1. Test program as a table.

Test number	Description	Input parameters
1.1	90° turn to port turning all thrusters of the IB. Towing notch not lubricated.	Stern RPM: 610 Bow RPM: 720 Thruster angles: STB 45° PS 40° CL -35°
1.2	90° turn to port turning all thrusters of the IB.	Same as above.
2.1	90° turn to port turning stern thrusters of the IB.	Same as above, excluding: CL 0°
2.2	90° turn to port turning all thrusters of the IB. Reduced thrust at stern, increased at bow.	Stern RPM: 340 Bow RPM: 910 Thruster angles: Same as in 1.1.
2.3	90° turn to port turning all thrusters of the IB. Thrust at stern increased, reduced at bow.	Stern RPM: 780 Bow RPM: 410 Thruster angles: Same as in 1.1.

The model scale tests in ice were performed with a convoy consisting of an icebreaker and an assisted merchant ship. Models used in the model tests are Icebreaker Polaris and a typical winter navigation capable merchant ship. Further in this study, the ships are referred as IB Polaris and ship II respectively.

Turning tests in level ice were tested with the combination. In the tests, 90-degree turns were driven and the whole turning diameter was extrapolated afterwards. This was done to maximize the usage of the available two model ice fields.

Notch towing in model scale is presumably affected by the towing notch – bow contact in addition to resistances and towing force. The influence of the towing notch was investigated by performing the first test with cleaned towing notch and bow. For the rest of the tests towing notch and ship II's bow was lubricated to reduce the friction so that the friction influence on towing force and turning diameter could be assessed.

Another presumably significant factor is whether the icebreaker's propulsion units are turned only at the stern or also at the bow. In addition, the distribution of propulsion power between stern and bow is presumed to be a significant factor. This was studied during the second model test day by varying thrust distribution between bow and stern, but also keeping bow propulsion unit straight in one test.

Test arrangement

The model tests were conducted in Aalto Ice Tank, Espoo Finland. The basin is a multipurpose basin with wave device and ice testing installations. The size of the basin is 40m x 40m with a water depth of 2.8m. The model ice is fine-grained, ethanol-doped ice.

Ship models

Model of Icebreaker Polaris is built in scale 1:21. She has three pulling azimuth thrusters, two in stern and one in bow. Total propulsion power is 19 MW.

Towed ship is a typical winter navigation capable merchant ship with conventional shaft line propulsion. Propulsion of ship II is not used during testing. Main parameters of the ships are presented in Table 2 below.

Table 2. Main dimensions of the ships in full-scale and model scale.

	IB Polaris	Model
L_{OA} [m]	110	5.24
B_{WL} [m]	24	1.14
T_{design} [m]	8	0.38
	Ship II	Model
L_{OA} [m]	146.6	6.98
B_{WL} [m]	23.7	1.13
T_{design} [m]	8.44	0.40

The towing notch is constructed to match full-scale towing notch in terms of attachment points. In addition to this, the model-scale towing notch has constraints that restrict the sideways movement of ship II bow.

Test measurements

Both model test days started with ice measurements. Target and measured values for both test days are presented in Table 3 below. Target thickness of 48 mm corresponds to 1 m in full scale. Target flexural strength 24 kPa corresponds to 500kPa in full scale.

Table 3. Model ice quantities.

Measured values			
Thickness (mm)	Flexural strength (kPa)	Compressive strength (kPa)	Elastic modulus (MPa)
46.8	29.9	46.1	88.5
45.8	31.4	51.5	88.5

During the first model test day two separate tests were conducted. During the second model test day three separate tests were conducted. The initial testing plan was followed during both test days.

Measurements for model ice properties and model tests were conducted according to ITTC recommendations. This applies for both measurement methods and for measured quantities.

MEASUREMENT DATA PROCESSING

Measurement data needed some processing for it being in suitable form to be compared to full scale. The scaling is based on geometric, dynamic, and kinematic similarity. For ice measurements only scaling was made, but with measurements made during tests some further processing was needed.

Location of the model was measured in x- and y-direction at 50 Hz. First the x- and y-components were calculated separately. After that common xy-component was calculated. This was further scaled to full-scale and converted to knots.

Towing force was measured in Newtons and needed to be converted to tons. The force was divided by gravitational acceleration and multiplied with 0.001 after scaling. Towing force was scaled by multiplying force with scale factor given to the power of three.

RESULTS

The most important results are turning diameters, average towing forces and average speed of the models during each test. These are presented in Table 4 below.

Table 4. Model test results as average values in full scale units.

Test #	Speed (kn)	Towing force (ton)	Turning diameter (m)
1.1	2.0	36.5	400
1.2	1.7	35.6	460
2.1	2.1	41.0	4300
2.2	0.5	42.6	790
2.3	1.8	54.5	410

Figure 2 shows the channel after the tests 1.1 and 1.2. The turning diameters are determined utilizing this picture. The icebreakers bow location when thrusters were fully turned to desired angles is marked to the figure. Figures show that the towing combination turned better in test 1.1 meaning that lubrication of the towing notch doesn’t affect turning capability. Figure 3 shows the channel and models after test day 1.

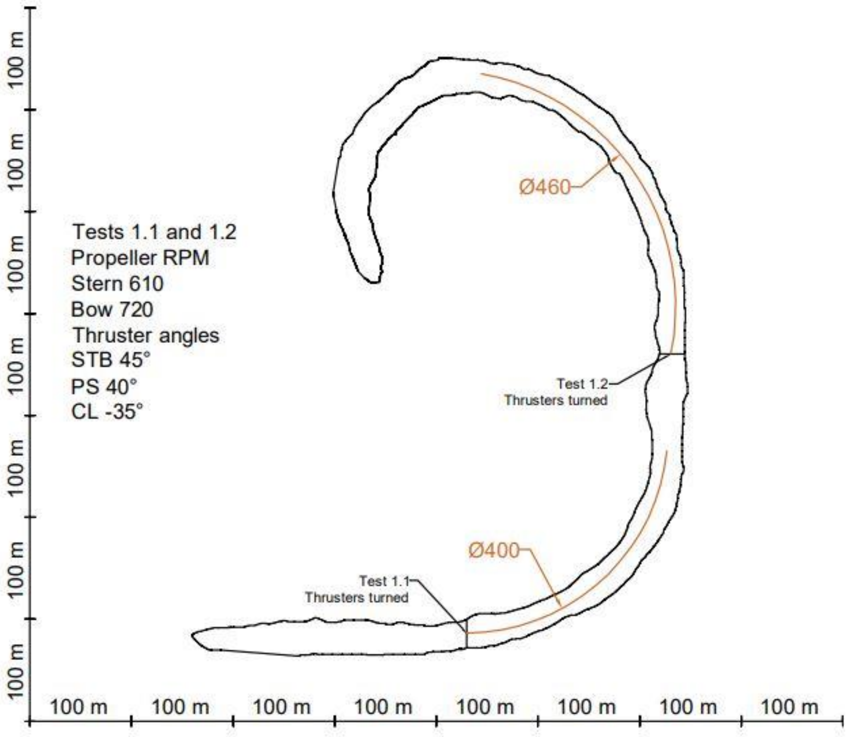

Figure 2. Turning track of model test day 1.

Figure 3. Ice field and models after test day 1.

Figure 4 shows the channel and turning diameters of tests 2.1, 2.2 and 2.3. The icebreakers bow location when thrusters were fully turned to desired angles is marked to the figure.

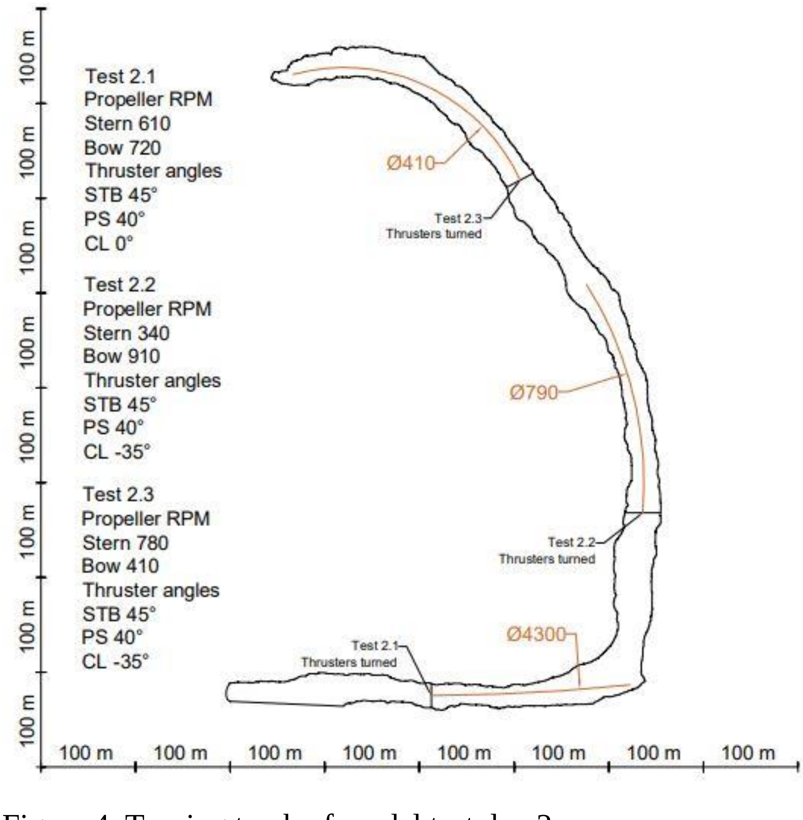

Figure 4. Turning track of model test day 2.

DISCUSSION

The experimental part included five model tests in ice in which turning tests were performed while towing. With tests 1.1 and 1.2 friction of the towing notch was studied. According to test results the friction of towing notch doesn’t significantly affect turning diameter or towing force. With tests 2.1, 2.2 and 2.3 the effects of icebreaker’s bow propulsion to turning was researched. In these tests it was noticed that icebreaker’s bow propulsion affects significantly to turning during notch towing. When bow thruster wasn’t turned, turning diameter of the towing combination increased over ten times compared to smallest turning diameter reached. Test 2.2 where propulsion power was added to bow wasn’t a success, because the models got stuck. In test 2.3 propulsion power was added to stern and second lowest turning diameter of the whole test series was reached although towing force rose compared to other tests.

In addition to these outcomes the functionality of 90-degree turning notch towing test was proven. A wider discussion on the topic and the research questions is found in Seppänen (2022).

CONCLUSION

Aim of this study was to develop a model test method for reviewing towing properties of an icebreaker based on ITTC procedures. The study was limited to notch towing situation where icebreaker is towing a merchant ship and the combination is turned.

In the beginning of the study theory of notch towing was described in terms of resistance and turning characteristics. In addition to this model test procedures and full-scale study was introduced. After that the research method was introduced.

In the experimental phase five separate model tests were conducted. These tests proved that the 90-degree turning notch-towing test is functional and that the results are in line with comparable results.

With this method clear results about icebreakers towing properties can be obtained, and it looks promising that this method can be used as such for example for comparing different concepts. However, the topic needs more research, as there is not much earlier research available on notch towing.

REFERENCES

Gong, H., & Matala, R. 2022. A study of full-scale measurement of channel widening by IB Polaris. China: The proceedings of the 32nd (2022) international ocean and polar engineering conference (ISOPE).

Heinonen, T. 2017. Notch towing operations. Winter navigation research board’s reports. ISBN: 978-952-311-747-1.

ITTC. 2021. Recommended Procedures and Guidelines – Manoeuvring Tests in Ice 7.5-02-04-02.2.

ITTC. 2021b. Recommended Procedures and Guidelines – Test Methods for Model Ice Properties 7.5-02-04-02.

Lindqvist, G. 1989. A straightforward method for calculation of ice resistance on ships. Sweden: Proc. 10th Int. Conf. Port and Ocean Engineering Under Arctic Conditions (POAC 1989).

Matala, R. 2012. Measuring of compressive strength of model ice. MSc thesis. Aalto University, Espoo.

Rosenblad, M. 2007. Increasing the safety of icebound shipping – WP4 operative environment (icebreaker operations). Helsinki University of Technology.

Seppänen, E. 2022. Model test method development to review notch towing properties of an icebreaker. MSc thesis. Aalto University, Espoo.

Suominen, M. 2020. Model Scale Testing in Ice – Lecture slides.

TraFi. 2011. Guidelines for the application of the Finnish-Swedish ice class rules. Available: https://sjofartsverket.se/globalassets/isbrytning/pdf-regelverk/guidelines_application_finnish-swedish_iceclass.pdf

Westerberg, V. 2014. EEDI and Finnish-Swedish Ice Class Rules. Winter navigation research board's reports. ISBN: 978-952-311-037-3.

Wilhelmson, M. 1996. The resistance of a ship in a brash ice channel. MSc thesis. Helsinki University of Technology.