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EXPERIMENTAL STUDY OF THE ICEBREAKING PROCESS OF AN ICEBREAKING TRIMARAN

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ABSTRACT
The primary goal of this paper is to present the results from a larger study of the icebreaking process of an icebreaking trimaran in level ice. Defining the icebreaking process of the trimaran enables further optimization of hull form and enables more efficient ship operations. Furthermore, the objective of this paper is to explain the small ice resistance of the icebreaking trimaran and to present how the distance between the main and side hull affect the ice resistance and the icebreaking process of the trimaran. The phenomenon was studied using ice model tests which were carried out in Aker Arctic's model basin using the latest icebreaking trimaran model. To achieve the most accurate visual data of the icebreaking process, a high-speed camera was used.

According to the visual observations, the icebreaking process at the middle hull of the icebreaking trimaran follows the icebreaking process of a traditional single hull ship. However, the icebreaking process of the side hull deviates significantly from the icebreaking process of a single hull ship. The side hull encounters an ice field with microcracks caused by the middle hull. These microcracks enable the side hulls to break the ice with a small resistance. The model test results show, that the small ice resistance of the icebreaking trimaran is due to a beneficial icebreaking process and the small size of the side hull compared to the middle hull. Optimum width is of course depending on the main dimensions of the various hulls. However, the optimum width for the concept studied in this case is around 50 meters when the ice resistance is determined relative to the width of the broken channel.

INTRODUCTION
Vessel traffic in the Baltic Sea is highly dependent on icebreaker support during the winter months. Typical large merchant vessels transiting in the area, such as Aframax-tankers (B=42m), are considerably wider than the icebreakers (B=25m). Therefore it is sometimes necessary to use two icebreakers to open up a channel for these vessels, especially in harsh ice conditions. In addition to this requirement the increasing interest in Arctic resources creates a need for a solution which can create wider channels for larger vessels without increasing the propulsion power demand drastically. The simplest alternative would be to use two traditional icebreakers. This is however not cost effective for the owner and not nearly always feasible.

There have been multiple experiments and testing for multihull icebreaker concepts in Finland during the past 30 years. These concept studies have been conducted to achieve better channel width versus needed power for icebreaking. The first ice model tests were performed in 1986 by Wärtsilä Arctic Research Centre (WARC) with a twin-hull vessel concept. The icebreaking catamaran showed promising results and was proven to decrease the ice resistance in all tested ice conditions. Masa-Yards Arctic Research Centre (MARC) continued the testing and made the first ice model tests with a triple-hull vessel in 1992. The trimaran concept was developed further and in 2008 Aker Arctic and Finnish environmental center (SYKE) performed further ice model tests for an open water trimaran hull designed originally by Mobimar. Based on these tests Aker Arctic developed a new concept (Icebreaking Oil recovering Trimaran, IBOT) of icebreaking trimaran in 2011.In this concept, the hull form had been modified to suit better for icebreaking. In addition to various ice model tests, other comprehensive studies have been carried out for the icebreaking trimaran such as seakeeping tests, CFD-studies, oil spill recovery function tests and proper cross-deck dimensioning for both ice and open water loads (Valtonen, 2013, Heikkilä et al, 2015).

The main goal of this paper is to present the icebreaking process of an icebreaking trimaran in level ice. The larger study behind this paper was conducted by using ice model tests. The objective is to explain the icebreaking resistance of the trimaran based on results and visual observation from ice model tests. Based on the studies made for the icebreaking process the optimum breadth for one icebreaking trimaran concept is introduced. The optimum breadth was studied by varying the distance in y-direction between the hulls. All other main dimensions of the trimaran will remain constant. A straightforward method for calculating the resistance of an icebreaking trimaran was developed, but excluded from this paper. Derivation of equations for the calculation method can be found on the Master's thesis of the author (Mård, 2013), on which this paper is based on.

NEW CONCEPTS OF IB TRIMARAN

The Icebreaking Oil recovering Trimaran (IBOT)

The new concept was designed for two different purposes: a Baltic version and an Arctic version. The Baltic version presented in Figure 1, has a bow with better seakeeping characteristics. In contrast to the Baltic version the Arctic version is designed to break heavy ice to meet the needs of the more difficult ice conditions. The Baltic version of the IBOT was used in the model tests presented in this paper.

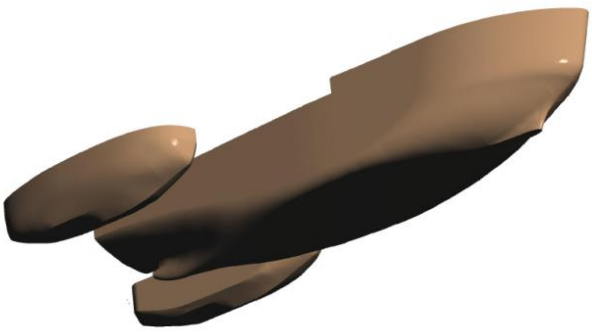


Figure 1. Hull form of the IBOT developed by Aker Arctic. (Aker Arctic, 2011)

Baltic Escort Icebreaker

Aker Arctic has further developed a new concept based on the IBOT Baltic Version. This concept has been developed as a result of extensive conceptual design, model testing in various ice conditions and seakeeping tests. The vessel is about 93 meters long and 42 meters wide. The main purpose for the escort icebreaker is to assist merchant vessels on its own operational area by breaking about 45 m wide channels in the main shipping lines during the winter months. The operational area for the vessel concept is the Baltic Sea. The main icebreaking direction is in ahead mode where the icebreaking capability of the vessel concept in level ice condition is at least 1.1 m. (Heikkilä, et al. 2014)

Harbour icebreaker Aker ARC 131

The harbour icebreaker concept presented in Figure 2 was developed to answer to a growing need to assist large vessels in ice infested harbours. The idea is that line icebreakers bring a convoy of ships close to the harbour and then turn around to pick up the outbound convoy, thus leaving the assisted ships into the care of smaller and more nimble harbour icebreakers with excellent manoeuvring features. These smaller vessels are then responsible for assisting the merchant vessel to the key side. This vessel is abt. 45 meters long and 26 meters wide and one of the design points for the icebreaker is to break 40 cm level ice at 7 knots. (Heikkilä, et al. 2014)

Figure 2. Aker ARC 131 Harbour icebreaker visualization. (Aker Arctic, 2014)

IB RESISTANCE BASED ON ICE MODEL TESTS

The Model

The model Baltic version was used to analyze the icebreaking process of the icebreaking trimaran. The trimaran itself is symmetrical in relation to its center line, but the side hull is asymmetrical. The main dimensions of the IBOT in full and model scale are presented in Table 1.

Table 1. The Main Dimensions of the IBOT in full and model scale.

Main Dimension	Quantity	Unit	Ship	Model
Trimaran				
Length overall	L_{tot}	[m]	81,1	4,59
Breadth overall	B	[m]	43,3	2,45
Breadth - water line1	$B_{1.wl}$	[m]	40,4	2,29
Breadth - water line2	$B_{2.wl}$	[m]	45,0	2,55
Breadth - water line3	$B_{3.wl}$	[m]	50,0	2,83
Breadth - water line4	$B_{4.wl}$	[m]	60,0	3,40
Design draught	T	[m]	5,0	0,28
Clearance 1	y_{h1}	[m]	4,6	0,26
Clearance 2	y_{h2}	[m]	6,9	0,39
Clearance 3	y_{h3}	[m]	9,4	0,53
Clearance 4	y_{h4}	[m]	14,4	0,82
Middle Hull				
Length overall	L_{mh}	[m]	73,8	4,18
Length - water line	$L_{mh.wl}$	[m]	66,7	3,77
Breadth	B_{mh}	[m]	17,5	0,99
Draught	T_{mh}	[m]	5	0,28
Side Hull				
Length overall	L_{sh}	[m]	29,4	1,66
Length - water line	$L_{sh.wl}$	[m]	25,4	1,44
Leveys	B_{sh}	[m]	6,8	0,38
Draught	T_{sh}	[m]	2,5	0,14
Model scale	λ	[m]	-	17,67
Propulsion power	P	[kW]	9000	-
Open water speed	v_{ow}	[m/s]	7,72	-
Friction coefficient (hull-ice)	μ		0,05	-

The clearance between the hulls y_h is defined as the distance between the flat side of the middle hull and flat inner side of the side hull. The definition of the clearance is presented in Figure 3. The middle hull and two side hulls are mounted together with aluminium beams.

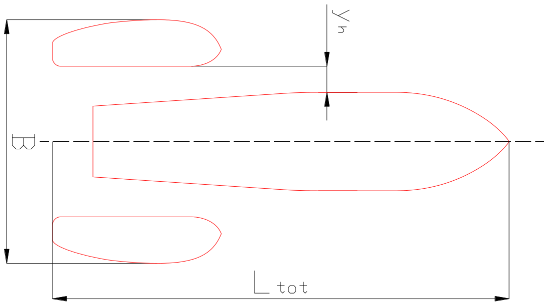


Figure 3. Definition of clearance y_h between hulls and total length of ship L_{tot}.

One of the most important research goals was to study how the position of the side hulls in y-direction affects the ice resistance and icebreaking process of the trimaran. Four different breadths for the trimaran were chosen: B_1 = 40.4 m, B_2 = 45m, B_3 = 50 and B_4 = 60 m. The chosen test runs including breadth and speed are presented in Table 2 marked by an x. The test run marked by a * is a benchmark from previous test series in 2011.

Table 2. Speed and Breadth matrix of the trimaran.

		Breadth B_S (m)			
Speed V_S (m/s)		B_{1WL} = 40.4	B_{2WL} = 45	B_{3WL} = 50	B_{4WL} =60
	V_1 =0.75	*		x	x
	V_2 = 2	x	x	x	x
	V_3 = 4	x	x	x	

Based on previous ice model test with the IBOT, the icebreaking resistance is practically constant when tested with small breadths 35-42 m. This is one of the reasons why three breadths above the design breadth were chosen for the study. The other reason is simply that larger breadths are more interesting as increasing the maximum breadth also increases:

- deck area
- oil recovery possibilities
- manoeuvring and
- width of the broken channel.

The widest version B_4 was selected in order to determine at which point the ice breaking process starts to deviate from the ideal ice breaking process and the resistance starts to increase considerably.

Models tests and program

The model tests were executed according to the standards of Aker Arctic. The experimental study was executed using towed ice resistance tests, basically meaning that the model is towed and the total resistance in level ice is measured. The pure ice resistance is then calculated by subtracting the resistance in ice-free water (i.e. open water resistance) from the total resistance. (Aker Arctic, 2008)

The test parameters were chosen based on the Baltic Sea ice conditions. The thickest ice in the Bay of Bothnia is typically around 80 cm (Kujala, 2007), which was chosen as the target value. The strength of first-year ice in Baltic Sea varies from 300-700 kPa. (Määttänen, 1998) Thus the target value 500 kPa was chosen for the ice strength. This target value is widely used for first-year ice.

To better understand how the speed affects icebreaking process of a trimaran, a range from 0.75–4 m/s was chosen (abt. 1.5–8 knots in full scale). The test program is presented in Table 3 including approximations of the distances of the test runs. All tests presented in Table 3 were also executed in open water to determine the open water for the trimaran.

Table 3. Three days test program in the model basin of Aker Arctic.

Level ice TEST	0 10 20 30 40 50 (m)		
Day 1	**Test 1.1** B_4 V_2	**Test 1.2** B_4 V_1	**Test 1.3** B_1 V_3
Day 2	**Test 2.1** B_2 V_3	**Test 2.2** B_2 V_2	**Test 2.3** B_1 V_2
Day 3	**Test 3.1** B_3 V_3	**Test 3.2** B_3 V_2	**Test 3.3** B_3 V_1

Equipment and Measurements

The following quantities were measured in the ice model tests: towing force, position of the model in x-direction, speed of the carriage and forces in x-, y- and z-direction acting on the starboard side hull. The forces acting on the side hull were assumed to be equal on both sides of the center line with adequate accuracy due to its symmetry in relation to the center line. In the towing tests, the model was positioned between two forks to prevent the model from yaw and sway. On the other hand, the model was free to roll, heave, surge and pitch. All measurement equipment is presented in Table 4 and Figure 4. The model tests were filmed from three different angles: under water beneath the model, under water from the side and above the water line on the side of the model basin. In addition to the standard angles, a high-speed camera and an extra HD-camera were used.

Table 4. Equipment presented in Figure 4.

No.	Equipment
1.	HD-quality video camera
2.	High-speed camera (200 Hz)
3.	Flash light and pulse sensor
4.	LEDs
5.	3 Kistler force sensors (50 Hz)
6.	Force sensor that measures the resistance of the whole model (50 Hz)
7.	Counterweight (10 kg)
8.	Fork
9.	Control room of towing carriage, Computers and Data Acquisition Software.

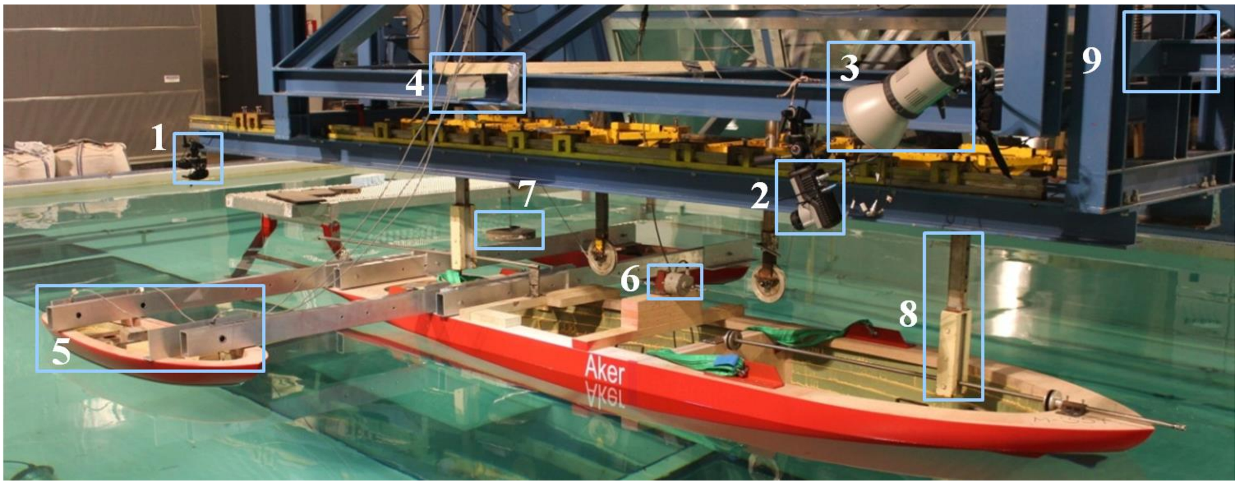


Figure 4. Outfitting of the IBOT model.

RESULTS

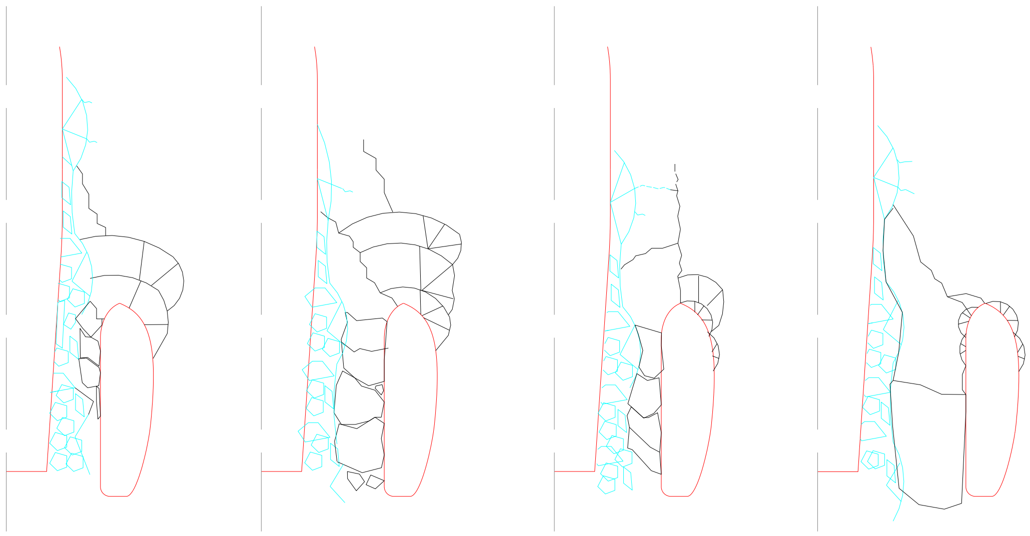
The icebreaking process of the icebreaking trimaran was primarily studied based on visual observations and secondly based on the resistance signal derived from the force sensors. The visual observations i.e. video footage and photos prove that the icebreaking process of a trimaran deviates considerably from a traditional single hull vessel's icebreaking process.

Firstly, according to the visual observations the icebreaking process of a trimaran begins with the middle hull encountering an unbroken ice field similarly to a single hull ship. The ice is broken as a result of bending cusps which are submerged along the buttocks. Finally, the broken ice pieces will slide to the sides and aft of the hull creating a broken ice channel behind the vessel. In previous studies it has been noted that microcracks emerge to the surrounding ice field, which happen to be extensively beneficial for the icebreaking process of the side hulls. These microcracks are very difficult to spot in both model and full scale

(Heinonen, 2009). However, the video footage from the high speed camera reveals that these microcracks occur in the ice field.

Secondly, the icebreaking process of the trimaran continues with the side hull encountering the ice field. The icebreaking process between the hulls can be divided into four different ideal processes (A, B, C and D), which are visualized in Figure 5. The icebreaking process of the side hull depends at least of the clearance between the hull and the speed of the model. All these idealistic processes have the following characteristics in common:

- The outer side of the side hull bow breaks the ice traditionally. Moreover, radial cracks are occur at the bow, propagating normal to the bow where after circumferential cracks emerge as a result of the bending force. These circumferential cracks often propagate all the way to the broken channel edge.
- On the other hand, the inner side of the side hull bow barely breaks any ice. The icebreaking occurring at the inner side of the bow consists mostly of radial cracks propagating all the way to the channel edge broken by the middle hull. Propagation direction of the radial crack depends highly on distance between the hulls in y-direction and direction, length and amount of microcracks in the encountered ice field and the speed of the model.
- Due to an increasing clearance between the hull, the ice floes and pieces broken in between the hulls flow smoothly between the hulls to the channel made by the trimaran.
- Underwater observations showed that side hull is almost completely covered by ice. However the inner side of the side hull is covered less than the outer side due to the asymmetric hull form.



a) *Process A* **b)** *Process B* **c)** *Process* **d)** *Process D*

Figure 5. Various icebreaking processes between the hulls of a trimaran defined on the basis of visual observations from model tests.

Process A occurs as the side hull is closer to the middle hull, i.e. when the breadth of the trimaran is 35–42 m. In this process, the ice between the hulls is broken mainly by the circumferential cracks caused by the outer side of the side hull bow. Occasionally, when the channel edge is further away at the bow of the side hull, radial cracks occur from the inner side of the side hull bow, propagating all the way to the edge of the channel. During this process, ice wedges between the hulls due to the small distance between the hulls. This phenomenon causes some additional resistance in form of friction.

Process B, which is presented in Figure 6 is the ideal icebreaking process for a trimaran. This process was most commonly observed in all of the tests and occurred with breadths between 40 and 50 m. The icebreaking pattern is clear and recurs as presented in Figure 7. This process begins with the inner side of the side hull bow breaking the ice between the hulls with a radial crack. As the side hull advances in the ice field, the circumferential crack caused by the outer side of the hull propagates all the way to the free edge of the broken channel. Several circumferential cracks emerge as long as the free edge is closer to the side hull than the actual channel edge broken by the middle hull. Once the free edge is far enough, the process will repeat itself.

Figure 6. The ideal icebreaking process of an icebreaking trimaran. Test run 3.2 B = 50 m and V = 2 m/s.

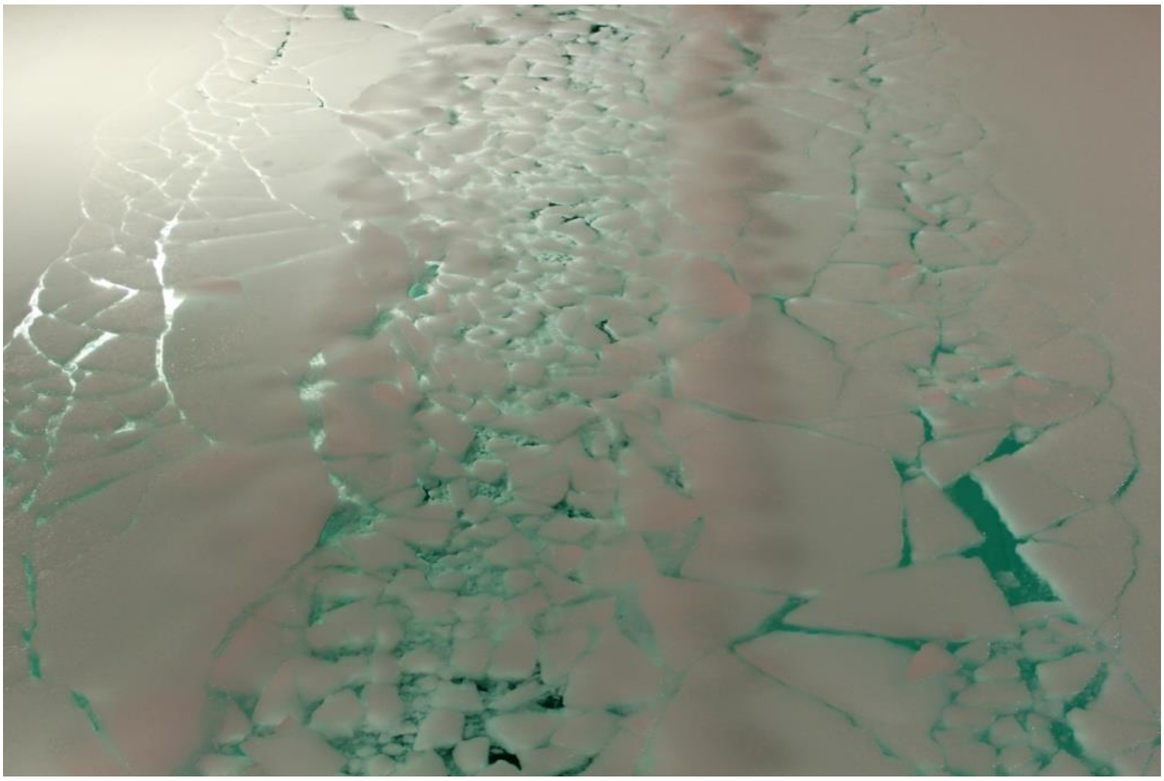


Figure 7. Broken channel and icebreaking pattern of the trimaran in test 3.2 (B = 50 m and V = 2 m/s)

Process C was also frequently observed during the model tests. It occurred in tests with breadths B_1, B_2 and B_3. The core of this process is that the side hull utilizes the microcracks caused by the middle hull. In some test runs, the radial crack initiated at the center of the side hull propagate almost straight ahead. As the crack has propagated to a certain point, it will meet the microcrack where after this crack will emerge. Is some cases not only radial microcracks were observed but also circumferential. These cases are presented in Figure 8.

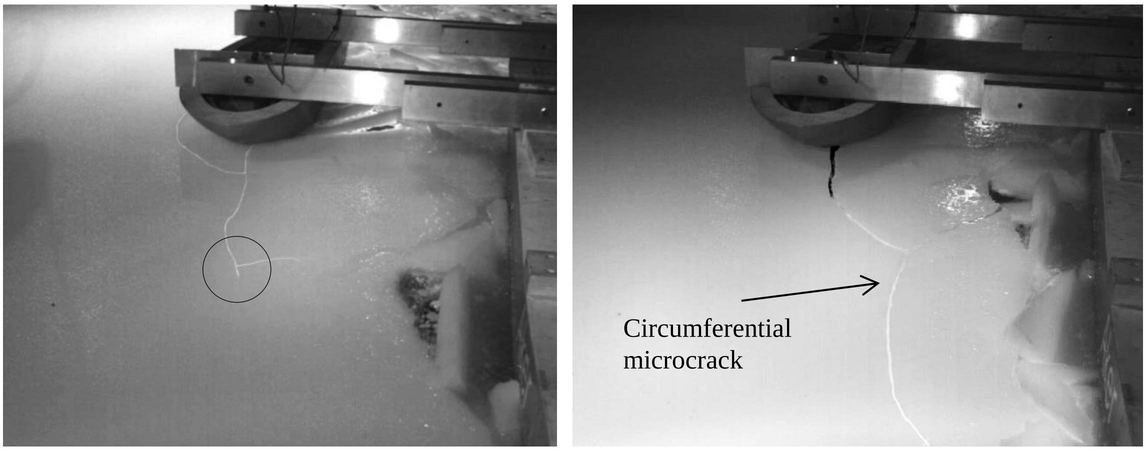


Figure 8. Microcrack occuring in the icefield between the hulls. On left hand side the radial microcrack occuring is marked by a black circle. On the right side a circumferential microcrack emerges.

Process D was defined for the case when the side hull is further away from the middle hull in y-direction. In this case the icebreaking process started to deviate from the previously defined processes and more to remind the icebreaking process of a single hull ship. However, in this case the side hull still breaks the ice between the hulls with radial cracks. Moreover, the frequency of the cracks is smaller and there are about 2–3 traditional icebreaking cycles before a new radial cracks emerges propagating all the way to the free edge.

Experimental icebreaking resistance

The results of the performance tests at 1.5 knots in ice are presented in Figure 9. In addition to the test results, the icebreaking resistance was predicted with the method developed by Lindquist (1989) for a similar traditional single hull ship to visualize and compare the benefits of the trimaran in level ice. The test results show that in 80 cm thick ice the ice resistance seems to be independent of the distance between the hulls when the width of the trimaran is between 35–50 meter (distance between hulls 2–9.4 m). The ice resistance of the trimaran started to increase significantly after the width was 60 meters. According to the model tests the icebreaking resistance of the trimaran increases linearly as a function of speed.

When the width of the trimaran is between 40 and 50 m, the ice resistance of the side hulls is approximately 25 % of the total ice resistance. This is very small when the additional broken channel width caused by the side hulls is taken into account. When the width is 60 m, the resistance of the side hull is approximately 41% of the total ice resistance. Figure 9 also shows that the resistance of the middle hull in independent of the position of the side hull in y-direction, i.e. the resistance of the middle hull is constant in all cases. The results of the test runs that were not presented in Figure 9 are presented in more detail in the Master's thesis of the author (Mård, 2013).

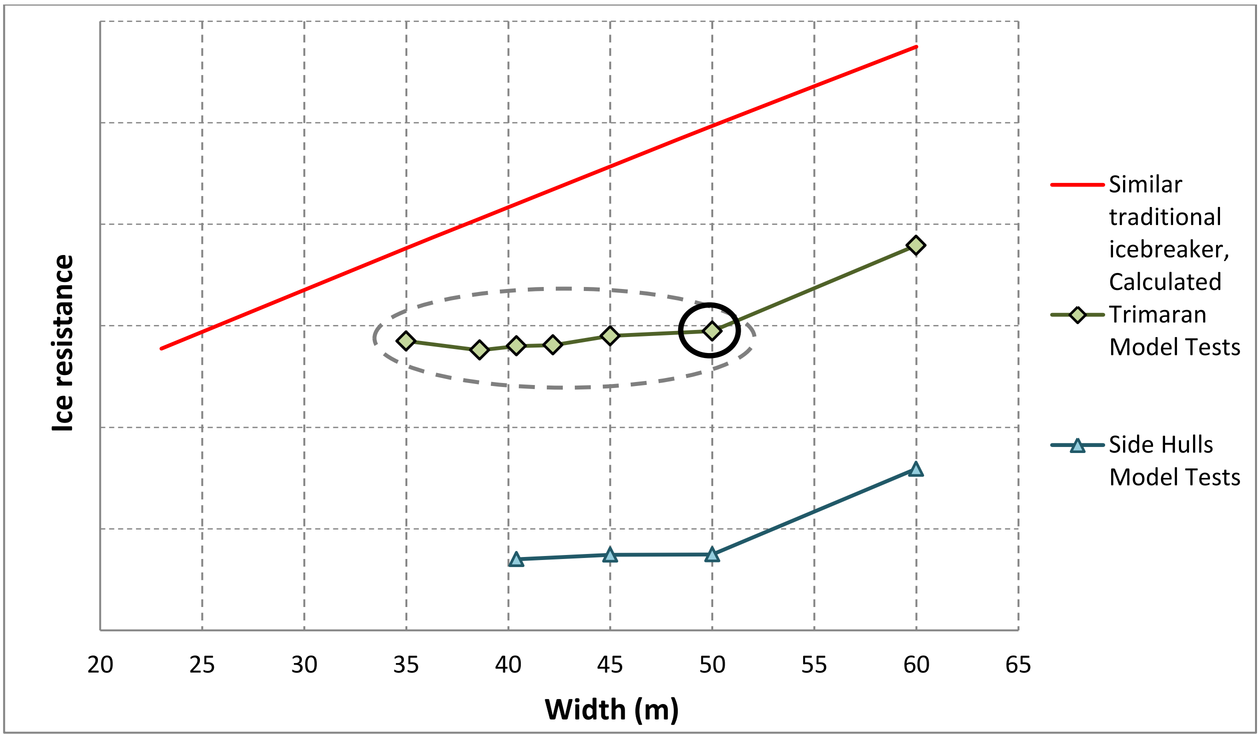


Figure 9. Comparison of ice resistances between a conventional Baltic icebreaker in 80 cm level ice and speed of 1,5 kn. (Similar traditional icebreaker, predicted with a method developed by Lindqvist (1989) and the Baltic trimaran (Model test results).

DISCUSSION AND CONCLUSIONS

Aker Arctic has been studying the possibility to break the ice with a multihull icebreaking ship for decades. Many concepts have been introduced and most of the studies have been concentrated on a Baltic version of the trimaran.

The icebreaking process of a trimaran was divided into four unique processes (A, B, C, and D) based on visual observations from ice model tests. Process D was only observed during the test runs with a breadth of 60 m. This process deviated from other defined processes and appeared as more independent icebreaking for the side hull. Consequently the resistance of the trimaran will increase significantly when the side hull is too far from the middle hull. Furthermore, the heave motion for the side hull was moderate in this process, which resulted in a kind of duck walk. On the basis of these observations, this concept with its main dimensions is not feasible with a clearance of 14.4 m or above.

The various ice sheets encountered by the middle hull (case I) and side hull (case II) respectively are presented in Figure 10. As a single hulled ship proceeds in ice, it encounters from an idealistic point of view a semi-infinite plate. This plate can be considered as infinite in three directions, which boundary conditions can be considered as fixed on adequate distance from the point force F.

In the case of an icebreaking trimaran, the side hull encounters an ice field which is infinite only in two directions from an idealistic point of view. In case II the boundary conditions in the transversal section differs from case I in that sense that the deflection is considerably higher in case II than in case I. Consequently, the ice will break in y-direction significantly easier to the freely supported direction. As a result, the icebreaking resistance of the side hull is small compared to the traditional icebreaker. In longitudinal direction the boundary conditions are the same in both cases.

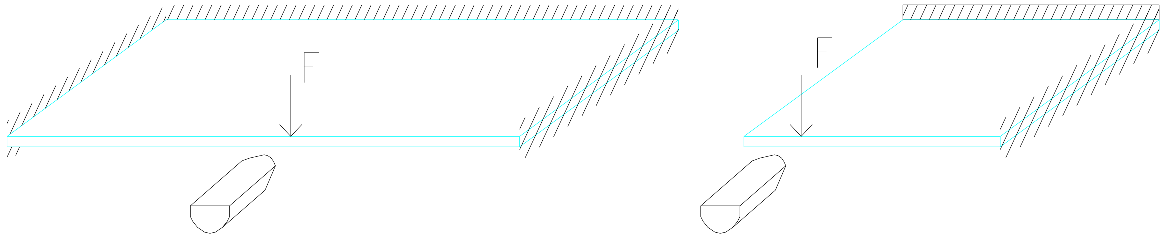


Figure 10. The various ice sheets encountered by the middle hull (Case I, left) and the side hull (Case II, right) of the trimaran).

In contrast to the middle hull, the side hull encounters an ice field with microcracks caused by the middle hull. These microcracks work for breaking the ice between the hulls. For small clearances between the hulls, the ice might wedge between the hulls. As a result some extra resistance is caused in form of friction.

However, in icebreaking processes A, B and C the side hull uses optimally the ice field containing microcracks. The ice edge caused by the middle hull is freely supported whereupon the inner side of the side hull bow breaks the ice between the hulls with radial cracks using little energy. The crack propagation in the ice field between the hulls is illustrated in Figure 11. The radial crack is formed at the bow (A) and propagated all the way to the freely supported edge (C), due to a stress concentration at the tip of the crack (B). Additionally, the microcracks (both radial and circumferential) caused by the middle hull emerge as the inner side of bow of the side hull breaks the ice between the hulls with radial cracks. The outer side of the side hull bow breaks the ice traditionally with circumferential cracks, which often propagate all the way to the free edge caused by the middle hull.

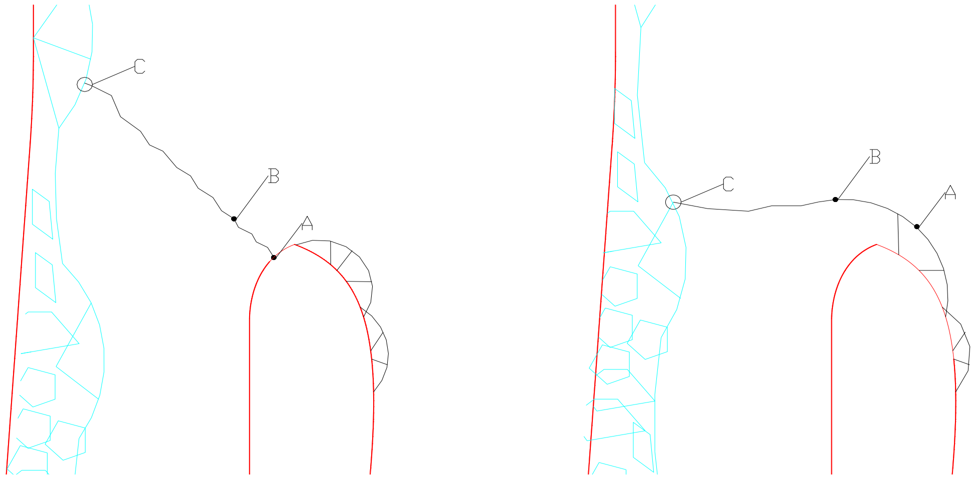


Figure 11. Visualization of the propagation of the radial (left) and circumferential (right) crack in the icebreaking process of the side hull.

After the studies made to define the icebreaking process for an icebreaking trimaran, it is clear that it is beneficial in many aspects such as the microcracks containing ice field encountered by the side hull. From the executed model tests it can be concluded, that the small ice resistance of the icebreaking trimaran is not only due to a beneficial icebreaking process but also the small size of the side hull compared to the middle hull. The optimum width of the icebreaking trimaran presented in this paper is around 50 m when the ice resistance is determined relative to the width of the broken channel.

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