Full-scale Ice Impact to an Azimuthing Thruster in Laboratory Conditions

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ABSTRACT
Ships navigating in winter conditions frequently come in contact with ice blocks floating on the waterways. The ice blocks can collide with the propulsion machinery of the ship. Especially the interaction between ice and ship azimuthing propulsion call for greater understanding.

Ice blocks can collide with the azimuthing propulsion units in many different ways, one of them being the propulsion unit hitting the ice block as the ship advances. This is an impact type loading case and the dynamics of the thruster and ship hull affect to the load response level obtained in this case. In a dynamic system, the damping is greatly affecting to the response level.

To study the dynamics and damping in an ice impact event, a full-scale test opportunity was found in an azimuthing thruster test bench. An impact test with a full-scale thruster and ice blocks was carried out in the laboratory with velocities corresponding to realistic ship operating speeds. In addition, numerical analyses of the ice-structure interaction were carried out and structural response was compared with the impact test measurements. Comparison between the simulations and the tests gave valuable information about the thruster dynamics during the ice impact.

KEY WORDS: Ice; Ice impact; Azimuthing propulsion; Simulation; Full-Scale measurement;

THE THRUSTER TEST STAND STRUCTURE

The Ice impact tests were conducted in a test facility where a full scale thruster can be run. The thruster is attached to a test stand structure where it is mounted like in ship bottom. Thruster is driven by an electric motor and the propeller shaft is linked to a generator. Thus, there is no real propeller rotating. The purpose of the thruster test stand is in general research of thrusters.

For the ice impact tests, a structure with rails, a wagon, weight, cable and pulleys was constructed. The ice impact with the thruster was carried out by placing the ice blocks into the wagon and then accelerating the wagon with a weight to a desired impact speed. By varying
the masses of the ice and wagon and the weight, the impact speed could be set as desired. The cable pulling the wagon was attached to a hook at the bottom of the wagon and released just before impact. This way, only the mass of the wagon and ice block took part in the impact. A drawing showing the thruster and the ice impact structure can be seen in Figure 1.

![Figure 1. Impact test structure](image)

**ICE IMPACTS TO THRUSTER - LABORATORY TESTS**

All together 12 impact tests were carried out. The number of tests was limited by the amount of available ice blocks and time. The most interesting test results with respect to ice impact are discussed here.

Ice blocks were frozen in a freezing container in insulated boxes. One of the ice blocks had temperature sensors to monitor the freezing process. First, the boxes were filled with tap water and the container temperature was set to -30 degrees Celsius. After about 10 days when it was monitored that the ice blocks have completely frozen, the container temperature was gradually brought to -2 degrees. During the freezing, all of the ice blocks developed some cracks, however these were not located directly at the contact area. Before the impact tests, the ice blocks were cut to correct size with a saw. See Figure 2 for ice block just before test.
Figure 2. Ice block before test. The impact area is in the middle of the block. One larger crack is visible at the top of the block.

Measurement setup in the thruster included the following sensors: Strain gauges in half bridge configuration to measure the bending force in the direction of impact on the thruster strut. Strain gauges in half bridge configuration to measure the shear force on the thruster strut in the direction of impact force. Three triaxial acceleration sensors on the thruster body. One triaxial acceleration sensor on the wagon to measure the accelerations, and thus the contact force, of the impacting ice. Two pulse sensors on the rails to measure the speed of the wagon just before impact. And finally, a high-speed camera to record the impact with speed of 2000 FPS. In addition, a laser distance sensor was used for final tests to see the amount of movement on the bottom of the thruster.

To calculate the response force of the thruster, a calibration was carried out by pulling the thruster from the impact area with a force sensor equipped winch. This way the measured strain gauge data from the strut could be transformed to response force.

Various thruster and test stand specific impact tests were done, but only the validation tests which could be compared to simulated results are discussed here. Table 1 lists these tests. The first test was a low speed test, which is interesting because in this test the ice block developed only minor cracks. In the second test the wagon had much higher speed and the ice block developed major cracks. The last test saw the use of a sharper hubcap, which purpose was to allow a larger indentation and thus lower the contact and the response forces in the impact.
Table 1. Test parameters

<table>
<thead>
<tr>
<th>Test number</th>
<th>Impact velocity [m/s]</th>
<th>Impact mass [kg]</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>139</td>
<td>Low speed test</td>
</tr>
<tr>
<td>2</td>
<td>5.5</td>
<td>136</td>
<td>High speed test</td>
</tr>
<tr>
<td>3</td>
<td>5.1</td>
<td>137</td>
<td>Test with sharper hubcap</td>
</tr>
</tbody>
</table>

In Figure 3 The post-impact state of ice blocks can be seen.

![Test 1](image1.png) ![Test 2](image2.png) ![Test 3](image3.png)

Figure 3. Ice blocks after impact

With the high-speed camera, the impact duration and ice crushing and cracking was possible to see. The duration of events in the video could be determined with an accuracy of 0.005 seconds. Below in figure 4, video screen captures from the test 3 are shown. During the impact in can be seen that the transparency of the ice block changes, which indicates cracks opening in the ice.

![Test 4](image4.png) ![Test 5](image5.png) ![Test 6](image6.png)

Figure 4. Screen captures of the high-speed camera from test 3.

An example of measured load during test 1 is presented in Figure 5. The curve on the left shows the overall timescale, that is five seconds after impact, and it is clear that the dynamic structure did not vibrate in this case after impact. On the right, a detailed view of the impact response shows how the load is varying during the impact event. A cyclic crushing process is assumed to take place and the structure local dynamics is contributing to this result.

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Figure 5. Measured response force time history for test 1. On the left, timescale of 5 seconds, showing impact and no vibratory behavior. On the right, detail of the impact event, showing that there is variation of response load during the impact event.

The thruster indentation into ice is determined for test 1 based on the size of the impact mark on the ice. Impact mark can be seen in Figure 6. The diameter of the marking was on average 110 mm, and the radius of the impacting steel part was 270 mm. When the maximum projection contact area with indenter radius \( r \) and indentation depth \( x \) is

\[
A_{\text{max}} = \pi (r_i^2 - (r_i - x_i)^2)
\]

(1)

It can be seen that with the maximum indentation projection area defined with the radius \( r_m \)

\[
\pi r_m^2 = \pi (r_i^2 - (r_i - x_i)^2)
\]

(2)

\[
x_i = r_i - \sqrt{r_i^2 - r_m^2}
\]

(3)

This results in 5.66 mm depth of indentation when the mark has 110 mm diameter and indenter has a radius of 270 mm.

For tests 2 and 3 the indentation could be measured directly because of much larger indentation. The indentation for test 2 was 85 mm and for test 3 175 mm.

Figure 6. Indentation mark on the ice after impact test no 1. Diameter on average is 110 mm.
Response force and contact force measurement results for tests 1-3 can be seen in Figure 7. It is clear that the test 2 has the highest contact and response forces, and that the thruster shows vibratory behavior after the impact. In comparison, in test 3, with even higher initial kinetic energy, the maximum response force is only 1/3 of the maximum response force of test 2 and the thruster does not oscillate notably after the impact. This difference is due to the sharper hubcap, which penetrates the ice block, and thus the dissipation of impact energy is divided to longer period. It should be noted here that for test 1 the thruster was equipped with force cylinders which essentially oppose the impact force. Thus, these cylinders affect the response results. For tests 2 and 3 these cylinders were removed.

The contact forces shown in the Figure 7 are calculated from the ice block acceleration measurements. For force levels this is not very accurate method, but gives some indication of force levels involved. Duration of the contact could be calculated accurately and was found out to be well in line with measurements from the high-speed camera footage.

Figure 7. Time histories of all the tests. All signals are filtered with low pass filter. For test 1 contact measurement data was not available. Contact and response force have opposite directions in the graph.

For test 2, a comparison test with identical input parameters was carried out. This test showed very similar response to test 2. Figure 8 Shows results of these tests.
ICE IMPACTS TO THRUSTER - NUMERICAL SIMULATIONS

One of the main objectives of the ice impact tests was to compare the measurements to numerical simulation results. Simulation code for ice block to thruster impacts was developed at VTT and described in detail in references (Kinnunen et al 2016, Kinnunen et al 2014, Kinnunen et al 2013, Kinnunen et al 2012, Tikanmäki et al 2010.)

The code models the ice impact with an average contact pressure over the contact area, combined with basic dynamics of the thruster structure. The contact area is based on the geometry of the structure. A simple spherical geometry can be used in normal ice block to thruster impact, but also other geometries are possible. The code also predicts the dynamic behavior of the thruster when thruster parameters are given. The system is solved with difference method in the time domain.

The main input parameters for the simulation are:

- Impact speed
- Impacting ice mass
- Mass of the thruster
- Thruster natural frequency
- Ice compressive strength

Impact speed and impacting ice mass were measured for the impact tests. The mass of the thruster means the effective mass of the first mode. Initially the mass was not known, and thus it was estimated, based on a modal test and confirmed by the impact test acceleration measurements. For ice compressive strength a value of 3 MPa was used.

Before ice impact tests, the first bending mode of the thruster was determined with experimental modal analysis. The modal analysis was done with impact excitation. The analysis gives the natural frequency, corresponding mode shape and damping of the mode. However, during the actual impact tests it was observed that the ice impacts caused vibrations, which were occurring at much lower frequency than the measured thruster natural frequency.
This implies that the dynamic behavior of the thruster stand structure is more complex. A likely reason for the change in the natural frequency is the splined coupling joining the propeller shaft and the loading generator. The splined coupling axial load carrying capacity depends on the torque of the shaft. Due to complexity of the structure, the exact behavior of the splined coupling and the influence on the dynamics of the thruster could not be investigated thoroughly.

With the measured input parameters, the code calculates time histories for the contact force at the impact and the subsequent response of the thruster structure. One such result can be seen in Figure 9.

\[
W = \int_0^{u(t)} F du
\]

where \( F \) is the contact force and \( u \) is the indentation to ice. Figure 10 shows the energy balance and indentation into ice for test 1 simulation. The \( E_{\text{kin}} \) limit is the initial kinetic energy. The gap between the \( E_{\text{crush}} \) and \( E_{\text{kin}} \) goes mostly to damping of the structure.
COMPARISON OF NUMERICAL SIMULATIONS TO MEASUREMENTS

Next, the comparison of simulations and measurements is discussed.

In Figure 11 a comparison is shown for test 1. Here it is notable that the simulated response force initially follows the measurement quite well, but predicts higher force. The simulated maximum response force is slightly over 15 kN and the measured maximum response force was around 10 kN. The vibratory behavior predicted by the code is not present. The smaller force and lack of vibratory behavior is most likely due to the attached force cylinders discussed earlier. It is likely that the cylinders initially have some room to move until they start to oppose the impact and thus cut the response force. 14 Hz natural frequency was used in the simulation, as this was measured in the modal analysis with force cylinders attached. Simulated indentation to ice was 8 mm, a 40% more than measured indentation.

![Graph of force vs time for test 1 comparison](image)

Figure 11. Test 1, comparison of simulated response and measurement results. Parameters: ice mass 139 kg, impact velocity 2.0 m/s and 14 Hz natural frequency of thruster.

In Figure 12 the comparison of simulation and measurements for test 2 is shown. It is noticeable that here the simulation and measurements give similar response force. Measurements and simulation show clear vibratory behavior after the impact. Indentation to ice in the simulation was 23 mm, 73% less than measured.

In Figure 13 The comparison of simulation and measurements for test 3 is shown. There is quite a large difference in the simulated and measured response. Simulated response force is now more than twice as high as the measured response. In addition, the response duration is longer. Simulation shows oscillatory movement of the thruster which is missing from the real test. It would appear that the longer contact, seen in Figure 7, does not excite the thruster natural frequency. Indentation to ice in the simulation was 110 mm, 37% less than measured in the tests.
Figure 12. Test 2, comparison of simulated response and measurement results. Parameters:
ice mass 136 kg, impact velocity 5.1 m/s and 16 Hz natural frequency of thruster.

Figure 13. Test 3, comparison of simulated response and measurement results. Parameters:
ice mass 137 kg, impact velocity 5.5 m/s and 16 Hz natural frequency of thruster, sharper
hubcap.
CONCLUSIONS

The results from the ice impact tests reveal some interesting points. It was observed that the thruster test stand used in these tests showed complex dynamical behavior. Due to this behavior some test results are hard to interpret and require more investigation. For example, it would appear that, in addition to thruster natural frequency, the natural frequency of the whole test stand also plays part in the dynamics of the system.

Some clear results were gained, such as the use of a sharper thruster hubcap which resulted in 70% lower response force levels when compared to standard hubcap. It was also observed that with nearly the same initial impact energy in tests 2 and 3, the thruster showed very different dynamic behavior because of different geometry of the indentor. In test 2 with standard hubcap the impact was short and force levels high, whereas in test 3 with the sharper hubcap the impact duration was longer and the response force levels lower. In test 2 the thruster showed clear vibratory behavior whereas in test 3 there was hardly any oscillation after the impact. This shows that even with same initial impact energy the response of the thruster can vary depending on the contact geometry, thruster natural frequency and other factors contributing to impact duration.

The comparison of test measurements to simulated results proved in some parts challenging. Test 1 results were influenced by the presence of force cylinders, which were believed to have affected the measured response levels. There was no major cracking or splitting of ice block in test 1. On the other hand, test 2 showed very good resemblance between simulation and measured results. Due to high impact forces, there was noticeable cracking in the ice blocks in tests 2 and 3. Ice blocks were partly or completely splitted in the tests. For test 3 it would seem that the sharper hubcap penetrated the ice block and splitted it completely which greatly affected the measured response force. The simulation does not take into account the cracking of ice blocks. It was observed by Kim et al. (2012) that unconfined ice blocks developed large cracks and failed by splitting during indentation experiments. After failure the ice was not able to absorb more energy.

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REFERENCES


