POAC'13
Espoo, Finland

Proceedings of the 22nd International Conference on
Port and Ocean Engineering under Arctic Conditions
June 9-13, 2013
Espoo, Finland

FULL-SCALE MEASUREMENTS ON BOARD PSRV S.A. AGULHAS II IN THE BALTIC SEA

Mikko Suominen [1], Jouko Karhunen [2], Anriëtte Bekker [3], Pentti Kujala [1], Mikko Elo [4], Rüdiger von Bock und Polach [1], Håkan Enlund [5], Sami Saarinen [4]

[1]Aalto University, Espoo, FINLAND

[2] University of Oulu, Oulu, FINLAND

[3] University of Stellenbosch, Stellenbosch, SOUTH AFRICA

[4] Aker Arctic Technology, Helsinki, FINLAND

[5]STX Finland, Rauma, FINLAND

ABSTRACT

The presence of rich natural resources in Arctic waters continuously raises interest in marine operations in ice. Despite the availability of several full-scale measurements in ice-infested waters, knowledge of the impact of ice-structure interaction on the ship's hull and propulsion system as well as on the comfort of the crew and passengers on board is limited. This can be attributed to: (1) the fact that the effects of ice loading on the ship hull has not yet been related to prevailing ice conditions, (2) ice loading and the related response of the propulsion system is an almost unknown process and (3) vibration levels resulting from ship-ice interaction are not known. To increase the knowledge in these fields, full-scale measurements were conducted on the PSRV S.A. Agulhas II in the Baltic Sea during March 2012. Measurements on the following were obtained: (1) ice loads on the ship hull and propulsion system, (2) ice-induced structural vibration and noise, (3) whole-body vibration comfort, (4) ship dynamics in ice, (5) global ice loads, (6) underwater noise and (7) mechanical and physical sea ice properties. Furthermore, the effect of ship operations on the loads induced by ice on the ship hull was studied during a variety of ship manoeuvres.

This paper focuses on selected aspects of the conducted full-scale measurements, including: (1) the ice loading on the ship hull and propulsion system, (2) human comfort on board (3) mechanical ice property measurements, (4) the effect of ship operations on the maximum ice loads on different hull areas, (5) the natural frequencies and damping effects of the propeller shaft and (6) the possibility of the resonance of the propeller shaft's due to the sequential propeller blade impacts with ice.

INTRODUCTION

The interest in marine operations in Arctic waters is increasing due to the natural resources in the area. Ice conditions add additional challenges into Arctic ship design. The hulls and propulsion systems of these ships have to withstand ice loads during the product life-cycle as a performance requirement. Furthermore, the human comfort on board these vessels is an important issue as the passengers and crew live and work in this environment for extended periods of time. In order to take these aspects into account in the design, knowledge on the relationship between the ice conditions and ice loading on the hull and propulsion system and vibration and noise resulting from the structure-ice interaction is required.

The difficulty in predicting ice loads on a ship hull and propeller arises from the stochastic nature of ice strength properties and the hull/propeller-ice interaction process. As ice is formed in nature, numerous variables affect the mechanical and physical properties of ice. Despite the ice breaking process is ambiguous and ice loading on the hull is random, statistics based on full-scale measurements provide a means to estimate and predict ice loads. The limiting factor in earlier full sale measurements (see e.g. Kujala, 1989 and Kujala et al., 2009) is that ice conditions, such as ice thickness, have been observed visually, but not measured with the same accuracy as the ice loads. In addition, studies on ice-induced loads on the propeller and vibration and noise resulting from the structure-ice interaction are rare.

To improve the current knowledge of these topics, new full-scale measurements were conducted in the Baltic Sea on board a new Polar Supply and Research Vessel (PSRV), the S.A. Agulhas II, in March 2012. These measurements included: (1) ice loads on the ship hull and propulsion system, (2) ice-induced structural vibrations and noise, (3) whole-body vibration comfort, (4) ship dynamics in ice, (5) global ice loads, (6) underwater noise and (7) mechanical and physical sea ice properties. Ice conditions were observed visually and ice thickness was measured with an electromagnetic device (EM) as well as with a new stereo camera system. The mechanical properties of ice, such as the flexural and compressive strength, were also measured on samples extracted from the ice field.

This paper presents the findings of this collaborative research effort with respect to: (1) the mechanical properties of the ice encountered in the field, (2) the maximum ice loads resulting from manoeuvring tests in different hull areas, (3) propeller-ice interaction and the dynamic response of the propeller shaft and (4) human comfort as experienced by a seated occupant on the captain’s bridge while the vessel is performing ice-breaking operations. The effect of ship operations on the loads induced by ice on the ship hull was studied by performing a variety of ship manoeuvres. In addition, a ridge penetration test was performed for which the profile measurement is presented here. Further noise and vibration measurements, comfort studies and underwater noise are not discussed here. Statistical energy analysis was also performed to predict the structure borne noise in different areas inside the ship and the underwater noise levels. The methodology and results will be discussed in a separate paper.

INSTRUMENTATION OF THE SHIP

The full-scale measurements were conducted on board the PSRV S.A. Agulhas II which was built by STX Finland at Rauma Shipyard and was delivered in April 2012. The main dimensions of the ship are presented in Table 1. The ship was built to Polar ice class PC 5 and hull strength in accordance with DNV ICE-10. The S.A. Agulhas II is unique in that it is the first Polar research vessel with a passenger vessel certificate.

Table 1. The main dimensions of the S.A. Agulhas II.

Length, bpp.	121.8	m
Breath, mould.	21.7	m
Draught, design	7.65	m
Deadweight at design displacement	5000	t
Speed, service	14.0	kn

For the ice load measurements on the ship hull, three different hull areas were instrumented with strain gauges: the bow, bow shoulder and aft shoulder on starboard side (see Figure 1). At the bow, the ice load was measured on two frames. At the bow shoulder and aft shoulder, the ice loads were measured on three and four frames respectively. Ice loads affecting the frame can be determined by measuring the shear strains on the upper and lower part of the frame in question. From shear strain it is possible to calculate the shear stress and further determine the shear force when the structure geometry and material properties are known. The effect of the ice loads (on the frame between the sensors) can be determined by calculating the difference between the shear force of the sensors on the same frame by subtracting the measured shear force on the lower part from the upper one. In addition, the stresses in the hull's plating were measured at all areas (see Figure 1).

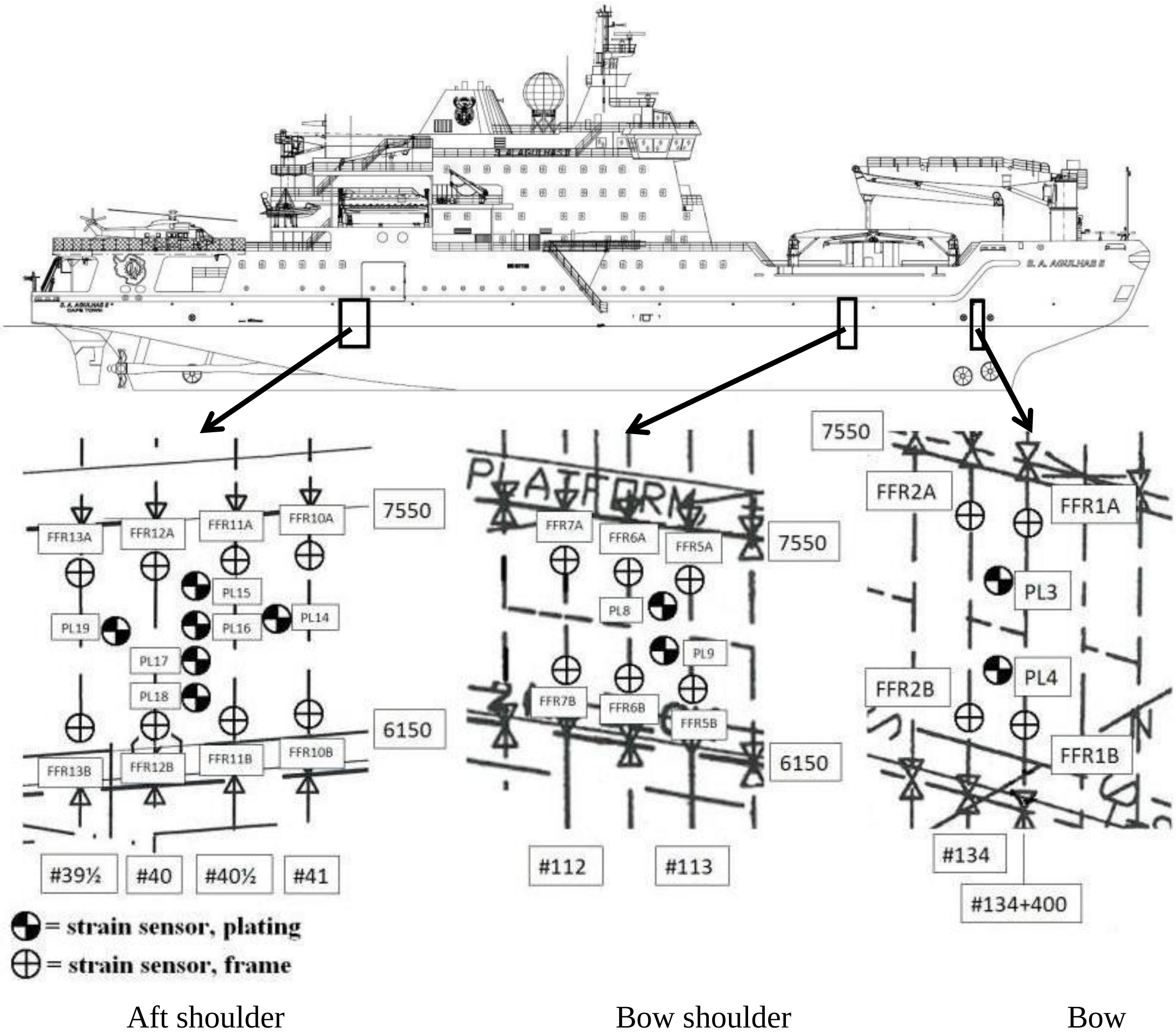

Figure 1. Strain gauge instrumentation at the bow, bow shoulder and aft shoulder areas.

For measurements of the ice loading on the propulsion system, the intermediate shaft line was instrumented with strain gauges. The strain gauges were mounted to measure the thrust and torque in the shaft line. This enables the determination of ice-induced loading on the propeller. The sensors installed for ice-loading measurements on the ship hull and shaft line and the data-collection system are permanent installations enabling continuous long-term measurements in the future.

Whole-body vibration comfort measurements were performed for a seated person on the Cleeman Dolphin seat, which is located on the bridge of the vessel (see Figure 2). The translational acceleration was measured in the vertical (Z), longitudinal (X) and lateral (Y) directions on the seat-mounting bracket which is bolted to the floor of the bridge. Acceleration measurements were also recorded on the interfaces between the occupant and the seat where vibration enters the human body. The measurements were based on a basicentric coordinate system for a seated occupant, as recommended by ISO 2631-1:1997 (ISO 2631-1:1997/Amd 1:2010). The measurement locations include tri-axial measurements on both the seat backrest (382 mm from the plane of the seat-seat) and the seat-surface (180 mm from the plane with the backrest) and a perpendicular (almost vertical) measurement on the seat footrest (see Figure 2). Recordings were made at a sample rate of 256 Hz using LMS TestLab 10A Spectral Testing software and a LMS SCADAS multi-channel data acquisition system. The duration of the reported measurements are limited to 16 seconds to enable the comparison of vibration levels with associated vessel manoeuvers.

Figure 2. A seated occupant on the Cleeman seat on the bridge of the vessel (on the left) and the placement of the seat-pad accelerometers for whole-body vibration measurement (on the right).

DESCRIPTION OF THE VOYAGE

The process of taking full-scale measurements started on the 19th of March 2012 from Rauma, Finland. Due to the mild winter, the ice cover existed only in the northern part of the Bay of Bothnia. The ship entered the ice-infested waters on the morning of the 21st and returned to the open water for the night (see Figure 3). A similar procedure took place on the 22nd. The measurements were ongoing while the ship was operating in ice and 24 hours of data was gathered on the ice loading of the hull and propulsion system. The time history of the ice thickness was recorded with the EM device and the stereo cameras during the operations in the ice conditions. Comfort measurements of the vibrations on the captain's seat were manually recorded during manoeuvres of interest.

Manoeuvring tests were conducted when the ship was operating in ice in order to gain more knowledge of the relationship between ship operations and the resulting ice loads and vibration and noise levels. The tests included: (1) turning tests in an intact ice field, (2) breaking out from the channel and (3) turning circle tests. In addition, straight forward tests were conducted in a channel and in an intact ice field as a reference. Furthermore, on 22nd

March the profile of a ridge was measured, after which a ridge penetration test was conducted with the vessel. After the 22nd, the voyage back to Rauma started and the ship returned to Rauma on 24th March.

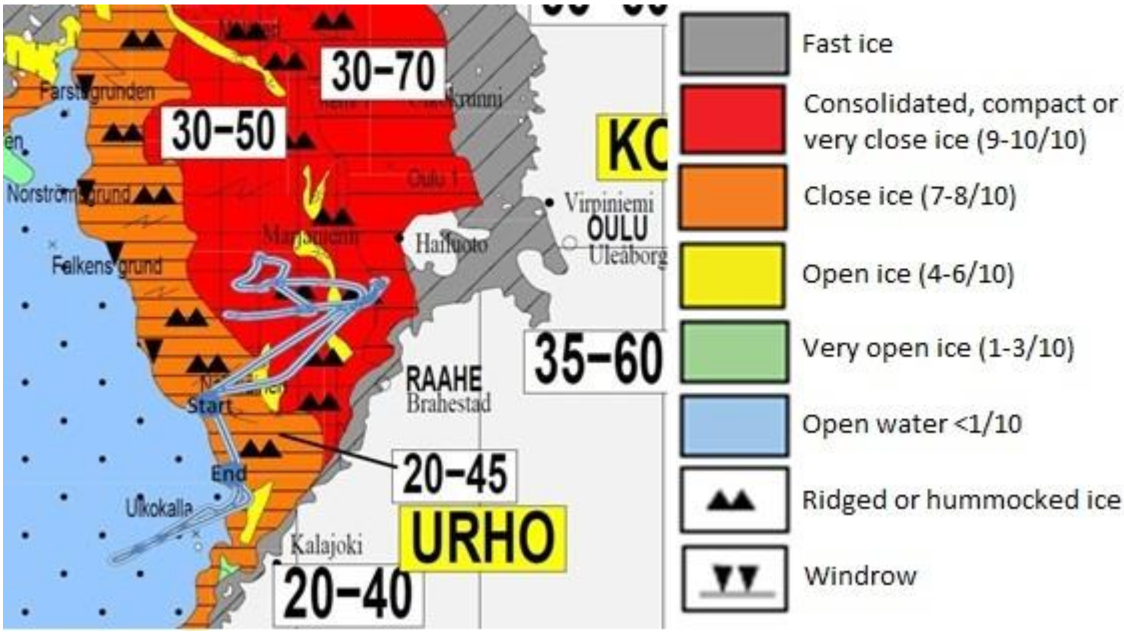

Figure 3. Ice conditions in the northern part of the Bay of Bothnia and the route of the ship on 21 March.

MEASUREMENT RESULTS

RIDGE PROFILE

As mentioned above, one ridge penetration test was conducted. The ridge profile was measured along three different lines ranging from one side of the ridge to the other side. The distance between the lines was 15 meters. The cross-sectional profile of the ridge was determined by drilling through the ridge with a motorised drill. The profile was measured at every one to two meters along the lines. The sail height and the freeboard of the ice were determined with a laser leveling device and by measuring the distance between water level and ice surface from the drilled holes with a 'beeper'. The profile of the ridge is presented in Figure 4. The sail height was found to be a maximum of 1.3 m and the keel reached a depth of almost 7 m.

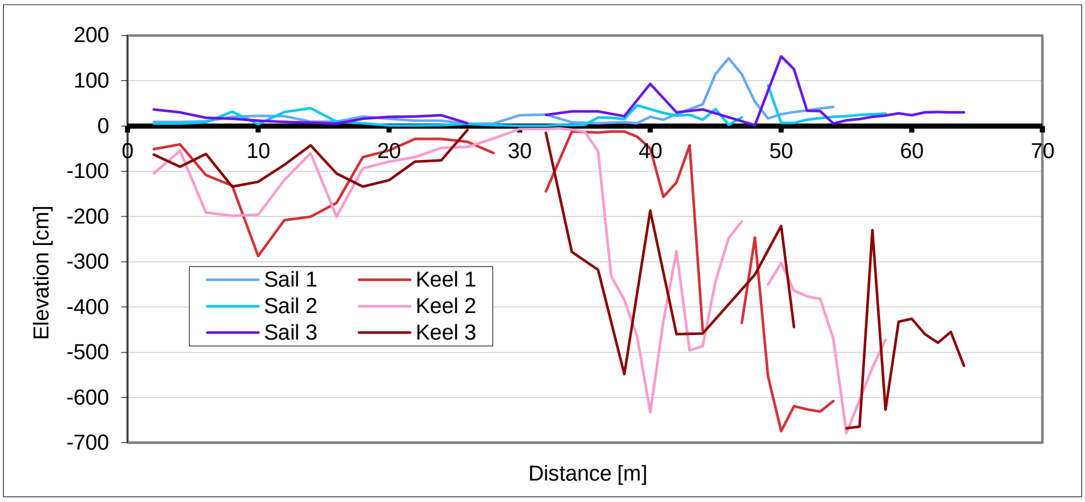

Figure 4. The profile of the ridge.

MECHANICAL PROPERTIES OF ICE

The samples for the flexural and compressive strength tests of ice were taken from approximately 40-cm-thick level ice at three different locations. The ice beams were cut from the ice field, lifted on board the ship and trimmed for the tests. The flexural strength of the ice was measured by performing three-point bending tests in an A-frame test rig. The beam was simply supported on both ends and it was loaded downwards from the middle. The force needed to break the beam was measured with a force transducer. The measurement setup is shown in Figure 5. The flexural strength of the ice (σ_f) was calculated from the measured force using beam theory at the center of the beam as follows:

$$\sigma_f = \frac{3}{4} \cdot \frac{(2F + G) \cdot L}{b \cdot h^2} \tag{1}$$

where F = force, G = gravity force $= b \times h \times L \times \rho \times g$, L = support span, b = sample width, h = sample thickness, ρ = ice density taken as 900 kg/m^3, g = gravity acceleration.

Figure 5. Test setup for obtaining ice flexural strength (left) and compressive strength (right) measurements.

Samples were taken from both the surface and the bottom layer of the ice. The measured ice flexural strength varied between 321 and 472 kPa and the average strength was approximately 404 kPa, which corresponds to spring ice in the Baltic Sea. The measurement results are summarised in Table 2. The ice strength value used in the ship design phase was 500 kPa.

The compressive strength of the ice was measured by crushing the trimmed samples with an electric compressor (see Figure 5). The force needed to crush the ice sample was measured with a load sensor attached to the clamp. The compressive strength is determined by dividing the maximum force by the cross-sectional area of the specimen. The compressive strength of ice was determined for the vertically and horizontally orientated specimens. The compressive strength varied between 0.65 and 1.98 MPa in the horizontal direction and between 1.41 and 2.79 MPa in the vertical direction, while the average compressive strengths were 1.28 and 2.02 MPa in the horizontal and vertical directions respectively. The measured values are typical for one-year brackish water ice. The results are presented in Table 2.

Table 2. Results of the mechanical sea ice property measurement tests.

	Compressive strength [MPa]		Flexural strength [kPa]
	Horizontal	Vertical	
Number of samples	17	8	8
Mean value	1.28	2.02	404.41
Standard deviation	0.38	0.52	59.17
Min	0.65	1.41	320.94
Max	1.98	2.79	471.57

ICE LOADS ON SHIP HULL

Manoeuvring tests were conducted during the full-scale measurements in order to study ice loading at different hull areas for different ship operations. The measured maximum ice loads on different frames for the associated manoeuvring tests are presented in Figure 6. Frames #134+400 and #134 were located at the bow area, frames #113, #112+400 and #112 were in the bow shoulder area and the rest of the frames were at the aft shoulder area. Label "Level" refers to level ice tests where the ship was operating straight ahead, "Turn" refers to turning tests in an intact ice field where the rudder angle was kept constant through the turning time and "Brchannel" refers to breaking out from the channel tests.

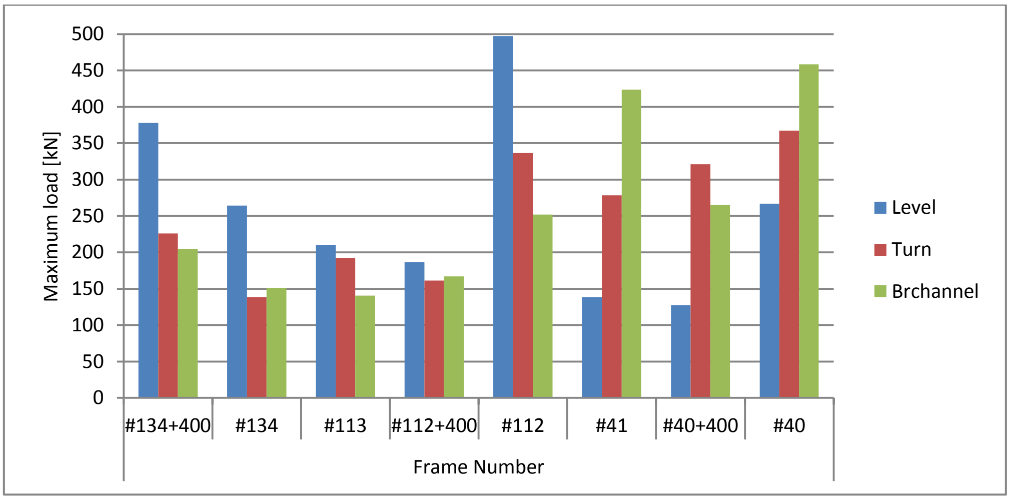

Figure 6. Measured maximum ice loads at the bow (frames #134+400 and #134), bow shoulder (frames #113, #112+400 and #112) and aft shoulder (frames #41, #40+400 and #40) area at manoeuvring tests.

As can be observed from Figure 6, the highest ice loads in the bow area (frames #134+400 and #134) occurred in straight ahead operations. In the bow shoulder area (frames #113, #112+400 and #112), the loads in different tests were at the same range, except in frame #112, where the measured maximum ice load in the straight ahead tests was significantly higher than the maxima in the other tests. What is notable is that measured maximum ice loads in the aft shoulder area (frames #41, #40+400 and #40) were higher in turning and breaking out of the channel tests than in the bow and bow shoulder areas. It was also observed that ice loads in the aft shoulder area during breaking out of the channel tests were of the same magnitude as the ice loads at the bow shoulder area in straight ahead operations.

MACHINERY

The thrust, torque and rotational speed of the propulsion shaft were measured. When the propeller blade hit a piece of ice, this shock excited the natural frequencies of the system. Figure 7 presents the excitation of the first (11.2 Hz) and second (46.2 Hz) torsional vibration modes. In a similar way, other natural frequencies can be found from the measured spectrums. During the design phase of the vessel, the natural frequencies of the propulsion system were calculated. A comparison of the calculated and measured natural frequencies is presented in Table 3. The measured natural frequencies seem to be a little lower than the calculated values. This is caused by damping and the mass of water, which rotates or moves with the shaft and propeller. In addition, the calculation model which has been used may have too few degrees of freedom.

Table 3. Calculated and measured natural frequencies. Two of the frequencies were not found during the ice trial.

Natural frequency [Hz]		Type
Calculated	Measured	
11.5	11.2	Torsional
49.6	46.2	Torsional
78.9	77	Torsional
11.1	9.2	Bending
20.85	Not found	Bending
27	27	Axial
69.8	Not found	Axial

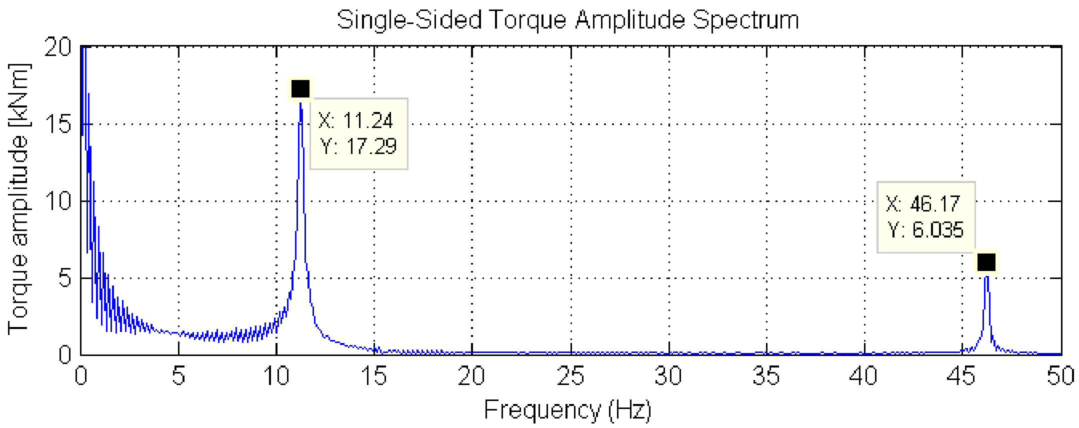

Figure 7. The lowest natural frequency of Torsional vibration 11.24 Hz visible in a measured spectrum.

PROPELLER ORDERS

The first propeller order corresponds to the number of propeller blades multiplied by the rotational speed of the shaft line. With the maximum rotating speed of about 140 rpm, the first propeller order is $4 \times 2.33\,Hz = 9.32\,Hz$. The second propeller order is twice the number of propeller blades multiplied by the rotating speed of the shaft line. With the maximum rotating speed, the second propeller order is $2 \times 4 \times 2.33\,Hz = 18.64\,Hz$. Figure 8 illustrates the rotational speed of the propeller shaft and the first and second propeller orders. The measurements revealed a double propeller blade impact, which could lead to resonance in some circumstances. The double propeller impact means that each of the propeller blades hit an ice piece twice during one full rotation of the propeller. Vibration caused by such a double propeller blade impact was of a similar order of magnitude to the one caused by the first propeller blade frequency, so no actual resonance was discovered. Figure 9 presents the torque and propulsion measured from the shaft line during the ice trial. With the help of these results it is possible to evaluate the torsional moments and possible over-torque that affect the propeller shaft when the blades hit the ice blocks. This will be done in future studies.

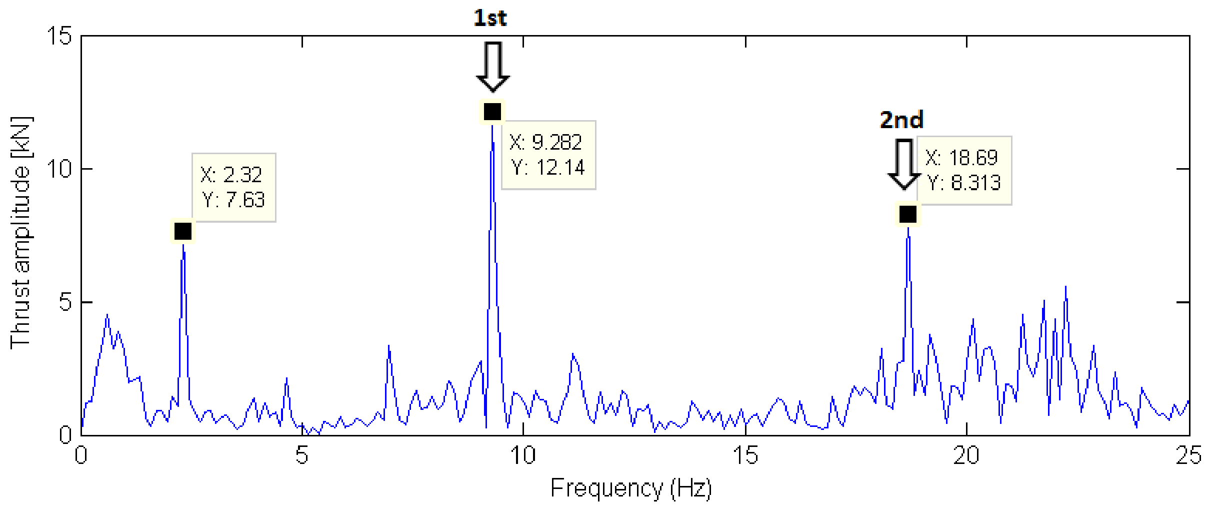

Figure 8. 1st and 2nd propeller orders visible in the thrust spectrum of the propulsion shaft. The rotational speed of the propeller shaft is 139 rpm (2.32 Hz).

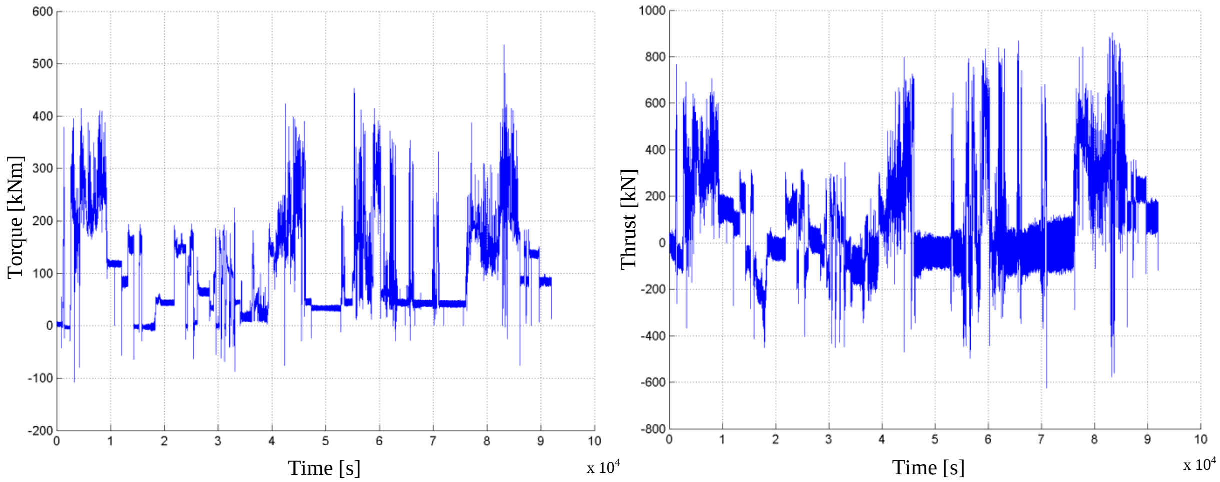

Figure 9. Torque (on the left) and thrust (on the right) measured from the shaft line during the ice trial.

HUMAN COMFORT

The multi-directional acceleration input, a_{Base}, at the seat base is quantified in terms of the vector sum of the tri-axial acceleration measurement (ISO 2631-1:1997/Amd 1:2010):

$$a_{Base} = \sqrt{a_{x_{Base}}^2 + a_{y_{Base}}^2 + a_{z_{Base}}^2} \tag{2}$$

where a represents the root-mean-square (r.m.s.) values of vibration acceleration and the subscripts x, y and z refer to the fore-aft, lateral and vertical direction of vibration, respectively. The magnitudes of the vibration exposures of the seated occupant are quantified in terms of overall ride values. The r.m.s. values of the frequency-weighted component ride values are first calculated at each interface with the human body and then multiplied with the square of a contribution factor. The resulting products of the component ride values and contribution factors are added in a vector sum to determine the overall ride value, as recommended by ISO 2631-1:1997/Amd 1:2010:

$$a_{Comfort} = \sqrt{a^2_{xWd_{SS}} + a^2_{yWd_{SS}} + a^2_{zWk_{SS}} + 0.8^2 a^2_{xWc_{SB}} + 0.5^2 a^2_{yWd_{SB}} + 0.4^2 a^2_{zWd_{SB}} + 0.4^2 a^2_{zWk_{FR}}} \quad (3)$$

The subscript, W, refers to frequency-weighted acceleration values and c, k and d represent the relevant frequency-weighting curves recommended for evaluation with respect to comfort of a seated person. SS, SB and FR respectively refer to the measurement locations on the seat surface, seat back and footrest.

Table 4 lists the translational vibration input at the base of the seat (a_{Base}) and resulting overall ride values ($a_{Comfort}$) for different ship manoeuvres. Figure 10 reports the magnitudes of the vibration input and the weighted whole-body vibration comfort component ride values for a seated occupant. Results show that vibration was prominent in the translational degrees of freedom during ship manoeuvres such as conducting a port-side turn in level ice at full throttle, reversing in a freshly broken channel with the rudder at an angle and cruising forward through level ice with ridges. During ice breaking, the maximum combined axis translational acceleration input on the floor of the captain's seat was found to be 0.4 ms^{-2} r.m.s. This corresponded with a maximum overall ride value for a seated subject of 0.15 ms^{-2} r.m.s. during a forward full-throttle turn in a level ice field. By comparison, the vibration experienced during this full-throttle turn in a level ice field is ten-fold that of the vibration exposure when compared to calm seas or quiet conditions. At the seat base, vertical vibration was more dominant than fore–aft and lateral vibration during ice-breaking manoeuvres. The Cleeman Dolphin seat transfers most vibration to a seated occupant vertically through both the seat surface and the footrest and longitudinally through the seat back. In subjective terms vibration levels are likely to be experienced as "barely noticeable" to "not uncomfortable" for all measurements obtained during the ice trail (ISO 2631-1:1997/Amd 1:2010)..

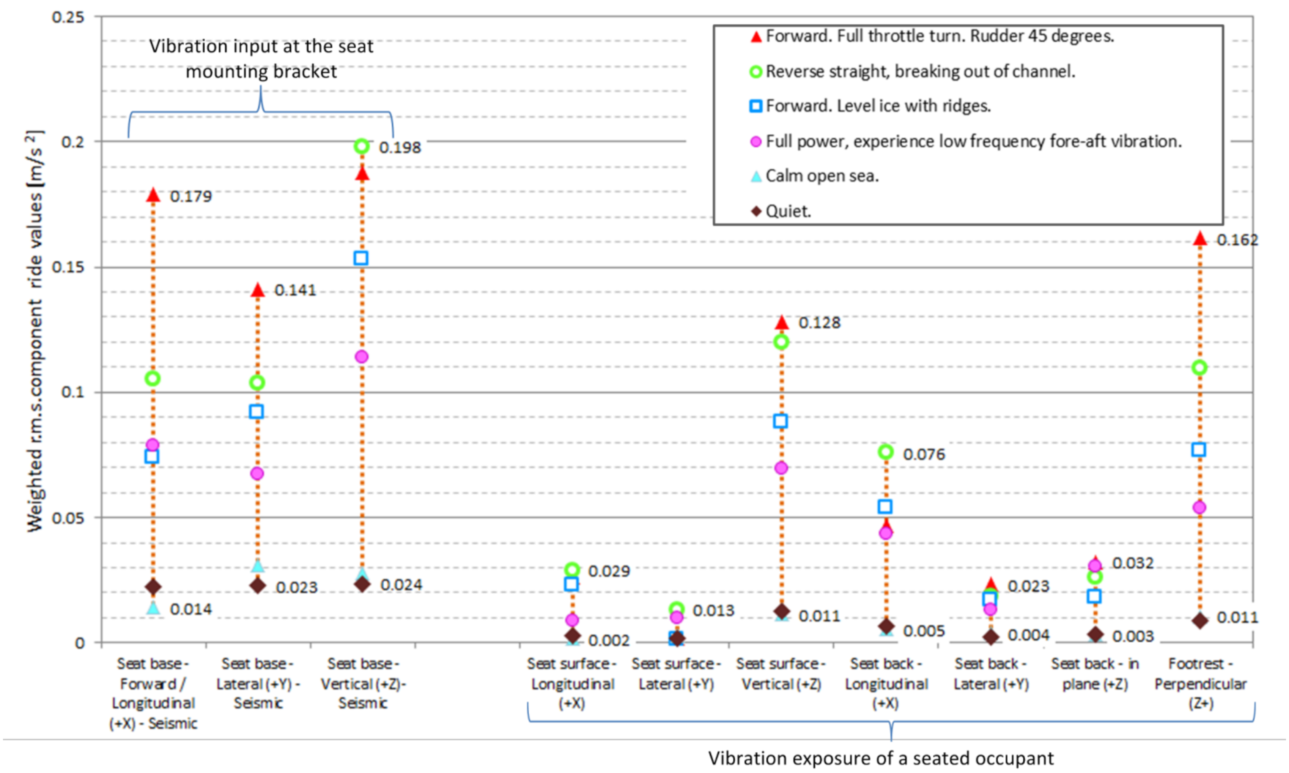

Figure 10. The magnitudes of the vibration input and the weighted component ride values for a seated occupant on the bridge of the vessel.

Table 4. Translational vibration input at the base of the seat and resulting exposures for different ship manoeuvres.

Vessel manoeuvre	a_{Base} [m/s²]	$a_{Comfort}$ [m/s²]
Forward. Full throttle turn. Rudder 45 degrees.	0.370	0.152
Reverse straight, breaking out of channel.	0.247	0.146
Forward. Level ice with ridges.	0.225	0.106
Full power, experience low frequency fore-aft vibration.	0.185	0.083
Calm open sea.	0.055	0.013
Quiet.	0.051	0.014

CONCLUSIONS

Ice loads measured on the ship hull in manoeuvring tests showed that ship operations clearly have an impact on the loading in different hull areas, as expected. Tests on turning and breaking out of the channel showed that the maximum ice loads are at the same level as in the bow area. It was expected that the loading would increase in turnings at the aft shoulder area, but the magnitude was higher than expected.

Measurements on the propulsion system showed that running the engine and small ice floats impacting the propeller blades generate torsional vibrations to the icebreaker's shaft line. The operating frequency of the electric engine; its multipliers; first propeller blade frequency, which is four times the operating frequency; as well as two of the three lowest natural frequencies of the torsional vibration could be seen clearly in the vibration spectrums when ice impacts occurred.

A double propeller blade impact, which is eight times the operating frequency and which could lead to resonance in certain circumstances, was also present in the measured results. Vibration caused by the double propeller blade impact is similar in magnitude to the one caused by the first propeller blade frequency, therefore no actual resonance was discovered.

The measured natural frequencies were lower than the calculated values. This is caused by damping and the mass of water, which rotates with the shaft and propeller. The double propeller blade impact and natural frequencies require further research, which will be done in the near future. In addition, the real torsional moments that affect the propeller shaft when propeller blades hit the ice blocks will also be studied in the near future.

The study of human comfort on board showed that during ice breaking, the maximum combined axis translational acceleration input on the floor of the captain's seat on the bridge was 0.4 ms^{-2} r.m.s. This resulted in a maximum overall ride value of 0.15 ms^{-2} r.m.s. as measured on the seat-occupant interfaces. The maximum combined axis translational acceleration input and overall ride value on the captain's seat was associated with a forward full-throttle turn in a level ice field. This constituted a ten-fold increase in the vibration exposure when compared to calm seas or quiet conditions. In subjective terms, vibration levels ranged from "barely noticeable" to "not uncomfortable" for the duration of the ice trail.

This paper presented the first results from the analysis of ice loading on the ship's hull and propulsion system, the mechanical properties of ice and human comfort on board. The processing and pre-analysis of the measurement data have been carried out. The next step and work for the future is to relate the different measurements to the ice conditions and link the measurements together.

ACKNOWLEDGEMENTS

The authors would like to thank Tekes (Finnish Funding Agency for Technology and Innovation) for the funding of the project and STX Finland for initiating the project. Furthermore, all the other project partners, namely Aalto University, the University of Oulu, Stellenbosch University, Aker Arctic Technology, Rolls-Royce, Wärtsilä, DNV, and the Department of Environmental Affairs of South Africa, are gratefully acknowledged. The research of the University of Stellenbosch is supported by the National Research Foundation and Department of Science and Technology under the South African National Antarctic Programme.

REFERENCES

ISO (International Organization for Standardization). 1997. Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration. Part 1: General requirements. ISO 2631-1:1997/Amd 1:2010.

Kujala, P. 1989. Results of long-term ice load measurements on board M/S Kemira during the winters 1985–1988. POAC 1989. Proceedings Vol. 2, Luleå, 12–16 June: 1118–1129.

Kujala, P., Suominen, M. & Riska, K. 2009. Statistics of ice load measured on MT Uikku in the Baltic Sea. POAC 2009. Proceedings, Luulaja, 9–12 June.