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Ilkka Perälä

PROPELLER SHAFT RESPONSE TO ICE EXITATION

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FOREWORD

In this report no 122, the Winter Navigation Research Board presents the results of research project ShaftRes, Dynamic response of propeller shaft due to ice impacts - Simulation and Ice trial measurements onboard R/V Aranda. Full-scale results of torque shaft measurements of propeller-ice interaction events were compared with simulated results to gain insight into the applicability of the ice milling excitation in the current version of the Finnish-Swedish Ice Class Rules.

The Winter Navigation Research Board warmly thanks Ilkka Perälä for this report.

Helsinki

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RESEARCH REPORT

VTT-CR-00039-22

Dynamic response of propeller shaft due to ice impacts - Simulation and Ice trial measurements onboard R/V Aranda

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Summary

R/V Aranda performed ice trials in February of 2020. On-board Measurements included torque measurements on the propeller shaft. In this study these measurements are compared to simulated torque response when using the ice milling excitation as given in the current Finnish Swedish ice class rules.

The model to simulate the shaft line torsional vibrations was build in Matlab Simscape, where time domain simulations can be carried out. Technical drawings and previous analysis by the shipyard were used as an input to the model creation.

Ice class IC ice torque excitation was used, as this matched with the mild ice conditions of the ice trials. R/V Aranda has an ice class IA. The comparison data from measurements was chosen as the maximum torques during the outbound and return voyages in ice channel. These two voyages were run with different speed, power and rpm settings so they offered two different comparison cases. In addition the reversing test in ice channel was also simulated as this had the highest torque levels of all measurements.

Comparison shows that the measured and simulated torque responses during the ice channel voyages are quite similar, with simulation giving slightly higher torque levels. In the reversing tests the measured torque levels were higher than the simulated ones for IC ice class. For IA ice class the results were quite comparable.

In conclusion, it can be said that the simulated and measured levels, when taking into account the ice conditions, in case of R/V Aranda are quite similar. Thus, the rule load matches the given ice conditions well. It also seems that the 41 % lower ice torque for ducted propeller is in this case justified. However, the torque during reversing tests in ice channel was much higher than in normal forward operation and might be something to study in the future in harsher ice conditions.

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Contents

1. Introduction

Maximum shaft torque due to propeller-ice interaction is important design criteria for ice-going ships. The Finnish-Swedish Ice Class Rules (FSICR) give ice class dependant design loads for the propeller that have to be fulfilled [1]. In addition to maximum static blade loads, there is a requirement to carry out a torsional vibration analysis (TVA) of the shaft line. The detailed requirements for the TVA are given in rule chapter 6.5.3.4 [1]. The vibration excitation due to ice comprises of four exaction cases, as seen in Figure 1. The propeller size, rpm and ice class define the amplitude of the vibration. As with all vibration cases, the worst situation is when the natural torsional frequency of the shaft line coincides with the excitation frequency. These resonance cases should not happen with normal operating rpm range. However, as the ice torque excitation frequency depends on the propeller RPM and number of propeller blades (blade order frequency) there is usually always some resonance cases which are passed through when accelerating from zero to operating condition.

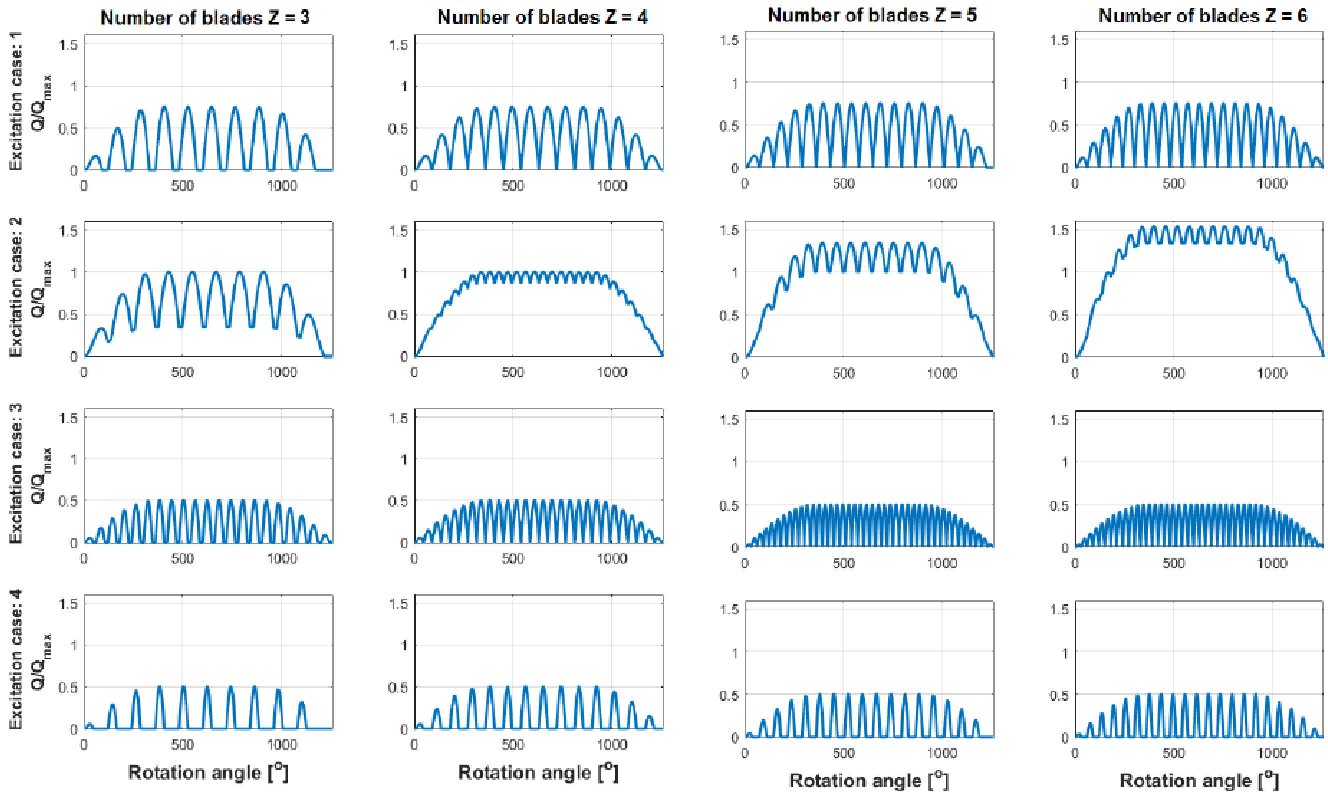

Figure 1. The shape of the propeller ice torque excitation sequences in ice milling events for propellers with 3, 4, 5 or 6 blades (FSICR 2017, figure 6-4).

The rules give lower ice torque levels for ducted propellers than open propellers. This is expected as ducted propellers are covered inside the duct from larger ice blocks. However, in harsh conditions ice blocks can completely block the duct which reduces the thrust of the propeller significantly. It can also increase the loads. In addition to torsional loads on the propeller and shaft line, the sudden ice torque causes a drop in the rpm as the engine cannot react to the increased load. In some cases the engine can even stall due to too high torque (usually problem with directly coupled diesel engines with fixed pitch (FP) propeller). This depends on the engine type and the dimensions of shaft line (shaft line component inertias). Currently in the rules the rpm drop and engine stalling is not considered.

In the past there has been quite a lot of calculations and measurements on ships to validate the loads given in the rules (see for example WNRB Research Report No 97). However, most of the measurements have been carried out with open propellers. One interesting test regarding the comparison of open and ducted propellers was carried out on icebreaker Karhu in 1986. Karhu has two shafts and the other shaft was open propeller and the other one was fitted with the same propeller but with a duct. The measurements are reported in [2].

In this project the goal is to compare shaft torque measurements from R/V Aranda to calculated ones from TVA. As the R/V Aranda has a ducted propeller this will give valuable information on the ice loads on ducted propellers.

2. Ice trial measurements on R/V Aranda

R/V Aranda is a research vessel owned by Finnish Environment Institute (SYKE). It is mainly used to make observations and research work at the Baltic Sea. Voyages are also made during winter in ice conditions.

The shaft torque measurement data was gathered during R/V Aranda ice trials on February 2020. Ice trials were carried out after the 2018 modifications to R/V Aranda hull and propulsion arrangement. The hull length was increased and the propulsion arrangement was changed from directly coupled diesel engines to diesel electric propulsion. This will enable the use of batteries and fuel cells in the future. R/V Aranda can be seen in Figure 2. during the ice trials.

Figure 2. R/V Aranda during ice trials on February 2020 at bay of Bothnia.

2.1 Instrumentation

The propeller shaft was instrumented with strain gauges for torque measurement and a pulse counter to measure the RPM. Typical full bridge torsional strain gauge arrangement was used, where two XY strain gauges are installed on opposite sides of the shaft at the same cross section. The telemetry devices transmitted the strain signal from the shaft and also provided power with wireless coil system. The whole data acquisition system consisted of imc Cronos PL2 and CRFX type amplifiers which were distributed around the ship. The other data, which were measured with the same system, included the ship speed and navigation data, as well as hull ice loads which were measured at the bow of the ship. Figure 3. shows the whole measurement system. More information on the RV Aranda propulsion arrangement is provided in chapters 3 and 4.

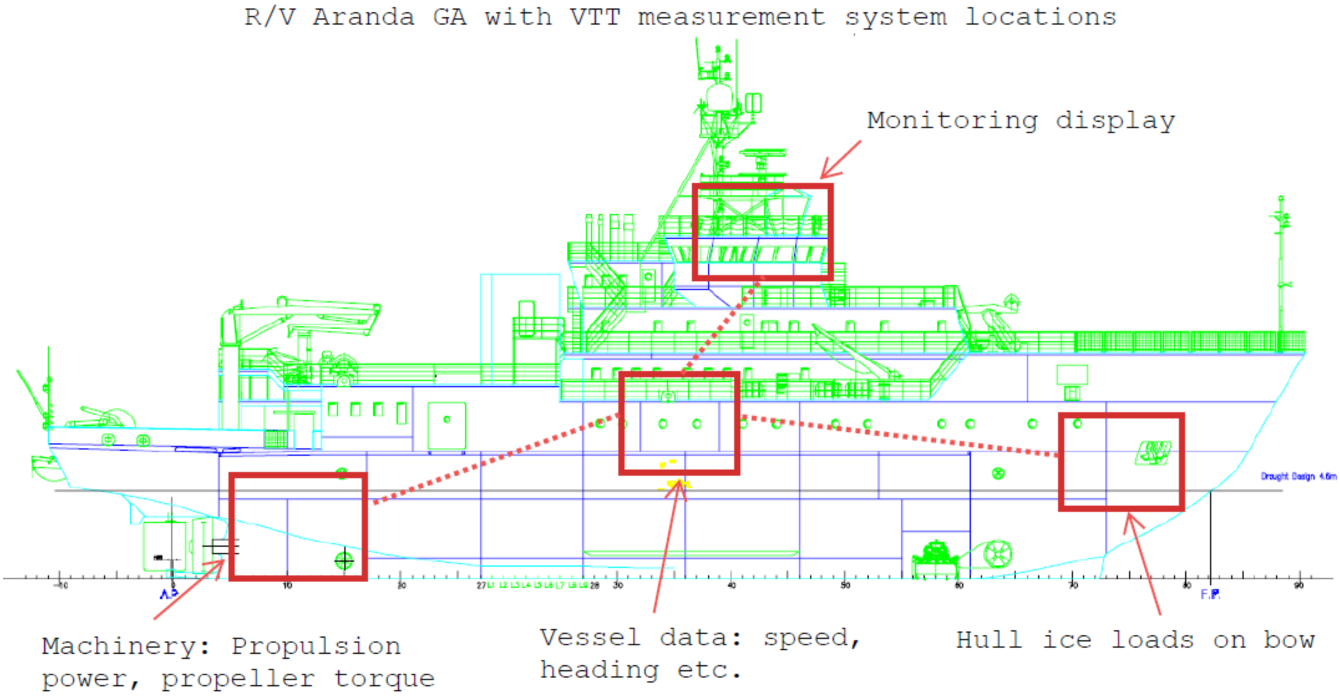

Figure 3. Measurement system during the R/V Aranda ice trials.

2.2 Ice trials

Data was gathered during the whole test leg and it included the transit voyages in ice channel. The ice trials included level ice breaking tests with varying power levels, turning circle tests in level ice, ice channel break out tests and reversing tests in an ice channel.

The ice conditions during the tests were mild/moderate, the measured level ice thickness was 30 - 40 cm. No ice ridges were encountered. It should be noted that R/V Aranda has an FSICR ice class IA where the required maximum level ice thickness is 0.8 m. The conditions during the ice trials were more comparable to maximum ice conditions for ice class IC (maximum ice thickness 0.4 m). Figure 4. shows the ice chart at the time of the ice trials as well as the R/V Aranda track and the area where the ice trials were carried out.

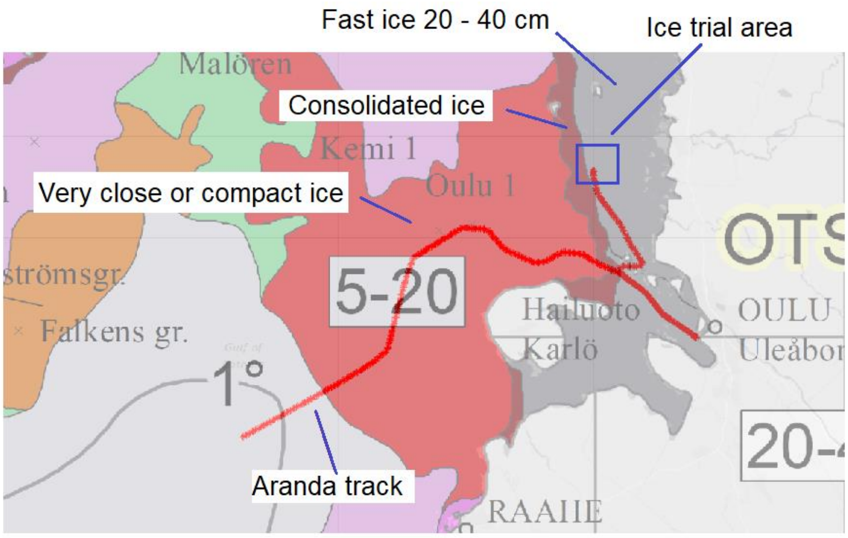

Figure 4. Ice chart from the time of ice trials 2.2 - 4.2.2020. Aranda track during the voyage to the ice trial area shown in red line. The voyage back to Oulu from the ice trials was the same (same ice channel).

Some time histories and peak distributions from the measurements can be seen in Figure 5, Figure 6 and Figure 7. The highest propeller shaft torques were recorded during the reversing tests in an ice channel. The speed of the ship was low, about 2 - 3 kn. It would appear that larger ice blocks hit the propeller during reversing than in forward operation. This is probably because the hull is not covering the propeller as well as in forward operation.

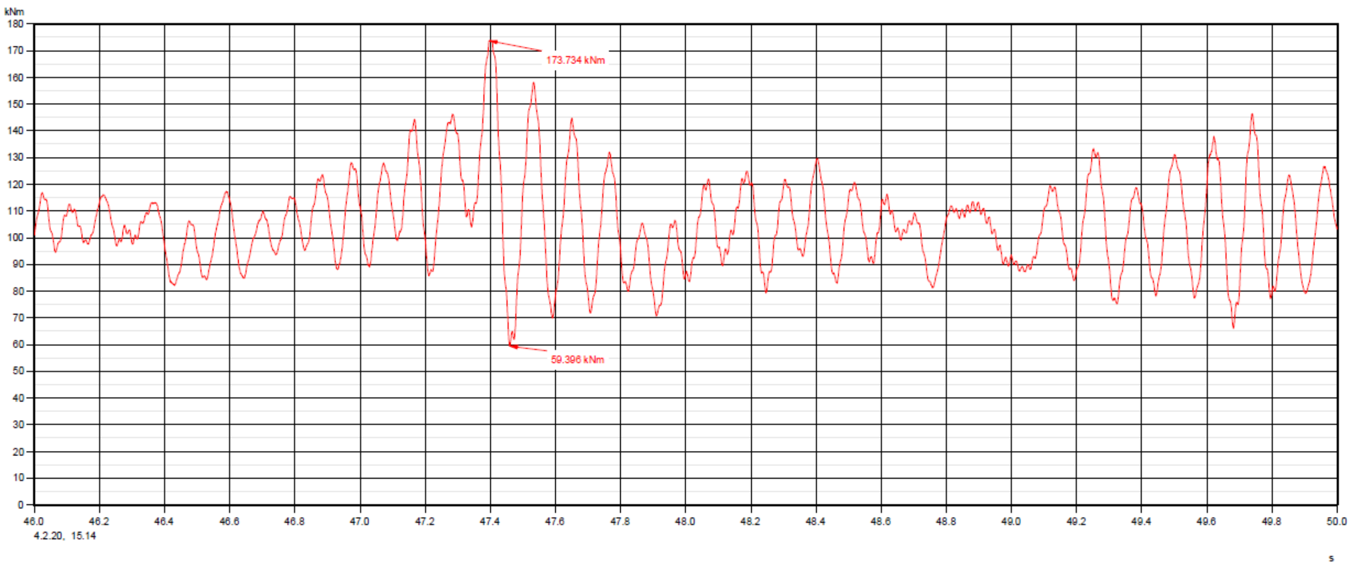

Figure 5. Highest measured propeller shaft torque during reversing tests

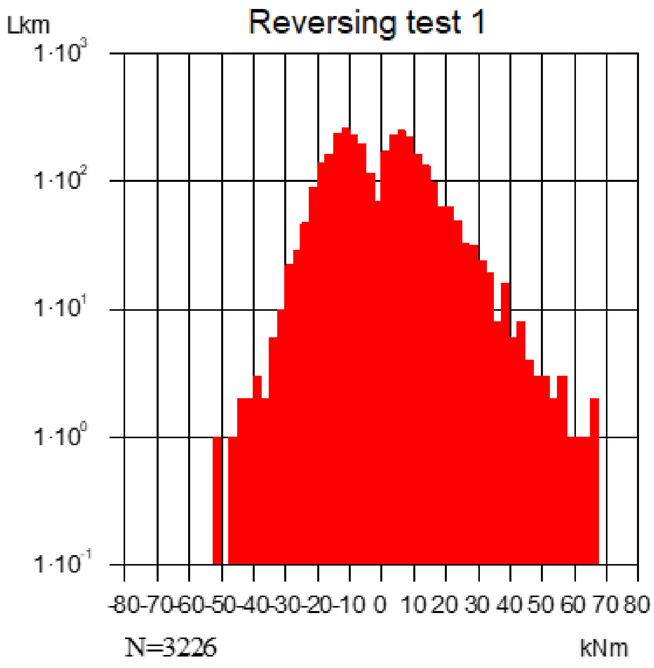

Figure 6. Propeller shaft peak torque distribution during two reversing tests. These are amplitudes around the mean torque.

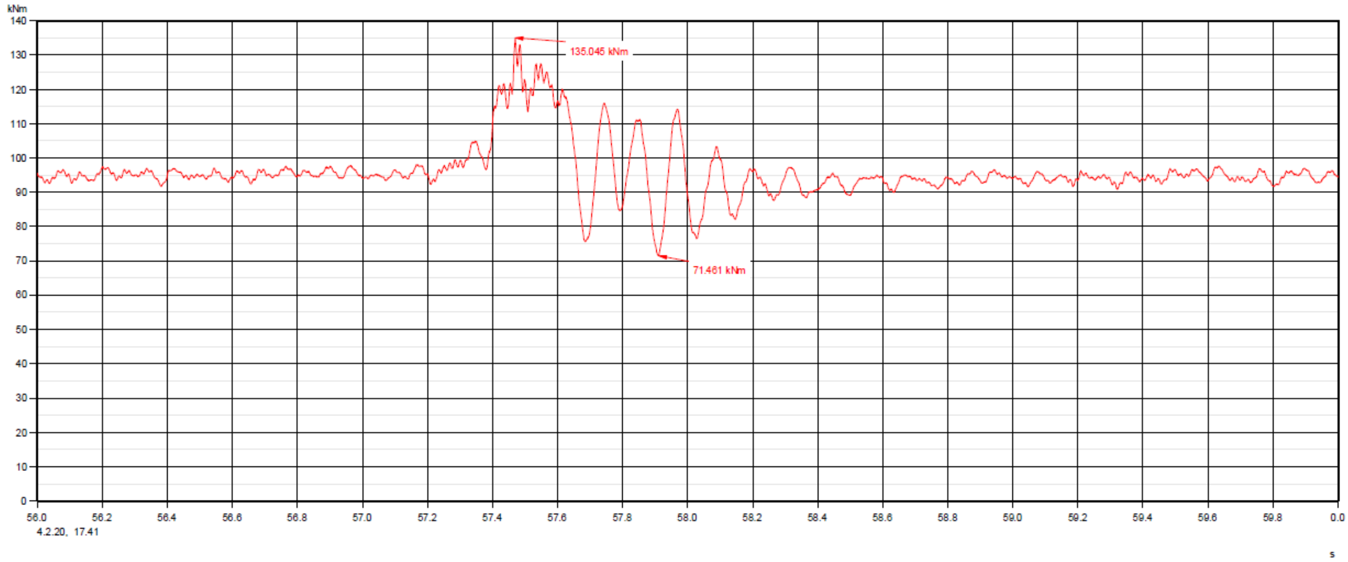

Figure 7. Propeller shaft max torque during forward operation in an ice channel.

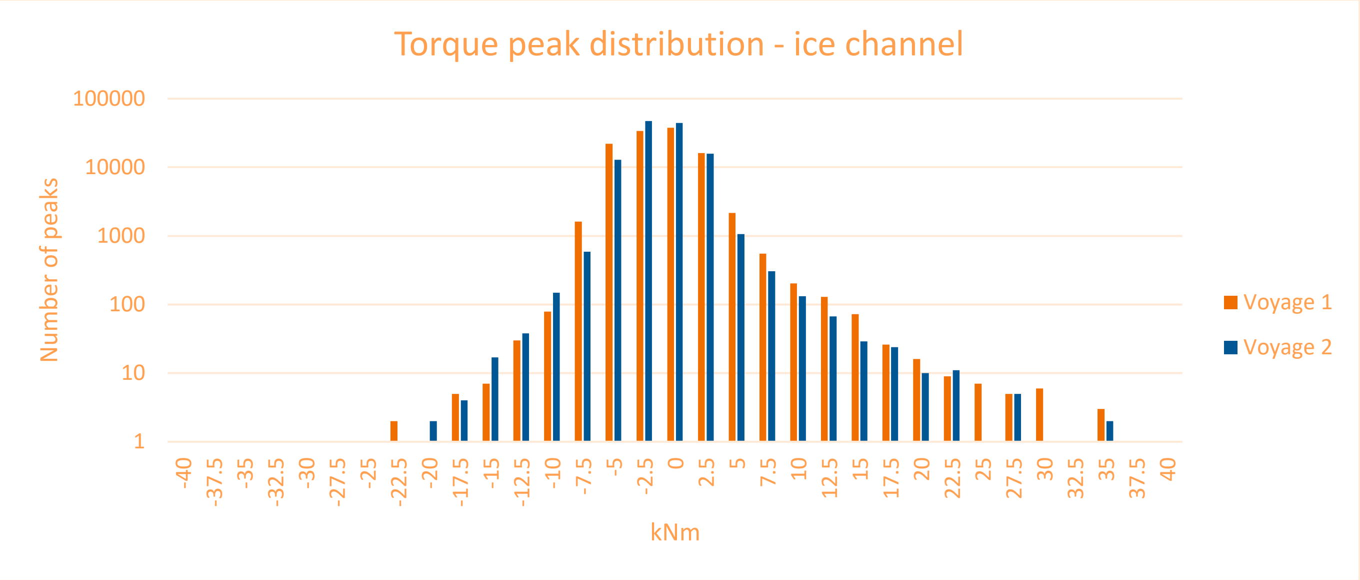

Figure 8. Propeller shaft peak torque distribution during transit voyages in ice channel. Amplitudes are calculated around the mean torque. Bin width 2.5 kNm. Voyage 1 is the outbound and voyage 2 is the return.

When looking at the torque peak distributions during transit voyages in ice channel, Figure 8, it is evident that the outbound voyage (1) has slightly larger amplitude peaks. The total number of peaks is quite similar (114 000 for voyage 1 and 122 000 for voyage 2), which is logical as the outbound and return voyages were essentially made in the same ice channel and had similar length. The comparison of ice induced large peaks (Amplitude over 15 kNm) shows that the voyage 1 has 60 % more higher peaks than voyage 2. The reason for this might be that the ice conditions had slightly changed in the ice channel during the one day of ice trials. Another reason might be linked to the dynamic behaviour of the shaft line. The voyage 1 was made with power setting of about 1200 kW and propeller RPM 176, whereas the voyage 2 was made with power setting of 2240 kW and propeller RPM of 215. The propeller RPM 176 is closer to the resonant region as shown in the next chapter.

2.3 Torsional natural frequency of the shaft line

One interesting characteristic to check from the measured torque data, is the lowest torsional natural frequency of the shaft line. This can be used to validate the simulation model later. Best way to excite the natural torsional frequencies of the shaft line would be to have a very sharp torque impulse on the propeller. However, this is usually not possible. Ice impacts on the propeller are not ideal, because in the ice milling process the blade frequency is dominant and the natural frequency of the shaft might not be noticeable.

The best way in this case is to choose a period of signal where the propeller is accelerated steadily from zero to normal operating speed and carry out a spectrum analysis of this ramp. The natural frequencies that are on this range can be seen as resonances in the torque signal. The excitation in this case comes from the weak pressure pulses of the propeller blades and thus the excitation frequency range is from zero to four times the max RPM (four bladed propeller). Example of this method is shown in Figure 9., although in this case the minimum speed was 80 RPM (5.3 Hz excitation). It was found out that the lowest torsional natural frequency of R/V Aranda shaft line is very close to 9 Hz, which means a propeller RPM of 135.

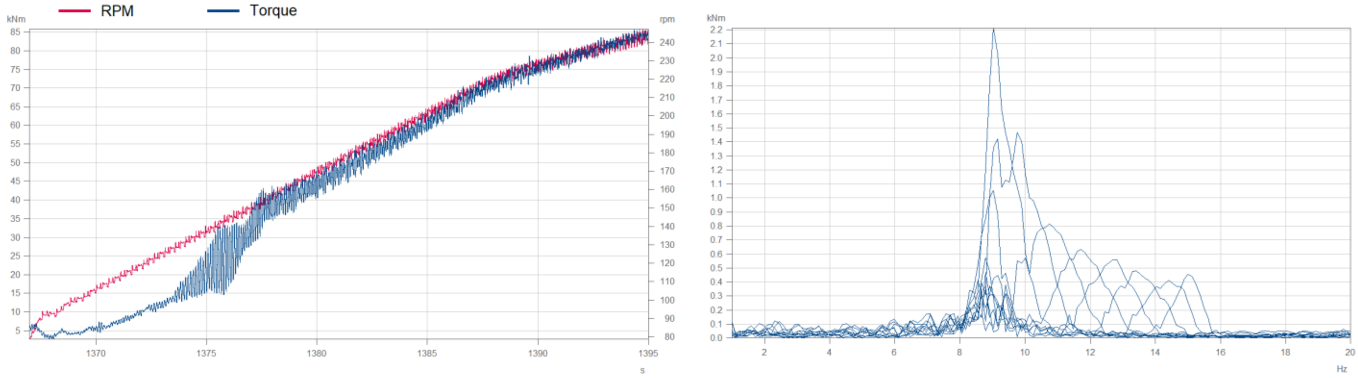

Figure 9. Determination of shaft line lowest torsional natural frequency. On the left time history of RPM and torque when propeller is accelerated from 80 rpm to 250 rpm. On the right spectrum analysis of the torque signal.

2.4 Determining the propeller KQ curve from the measurements

For the simulation model the propeller torque due to hydrodynamic forces has to be determined. Propeller torque and thrust characteristics are usually expressed with KT and KQ curves. KT meaning the thrust and KQ torque. In this case only the KQ curve is of interest. With KQ curve the propeller torque can be estimated if propeller RPM and ship speed is known.

KQ curve was first derived from measurements during the sea trials in open water. However, in ice conditions the KQ curve is different. According to [3] this is because of the increased viscosity of the water due to ice. Another reason might the used pitch of the controllable pitch propeller. Second KQ curve was then developed for ice conditions using the shape of the open water curve and measured points from the ice trials. Because the ice conditions can vary quite substantially the smoothed curve is only an approximation. However, it should give more realistic values, as the KQ in ice conditions is usually higher than in open water. Figure 10. shows the derived KQ curves.

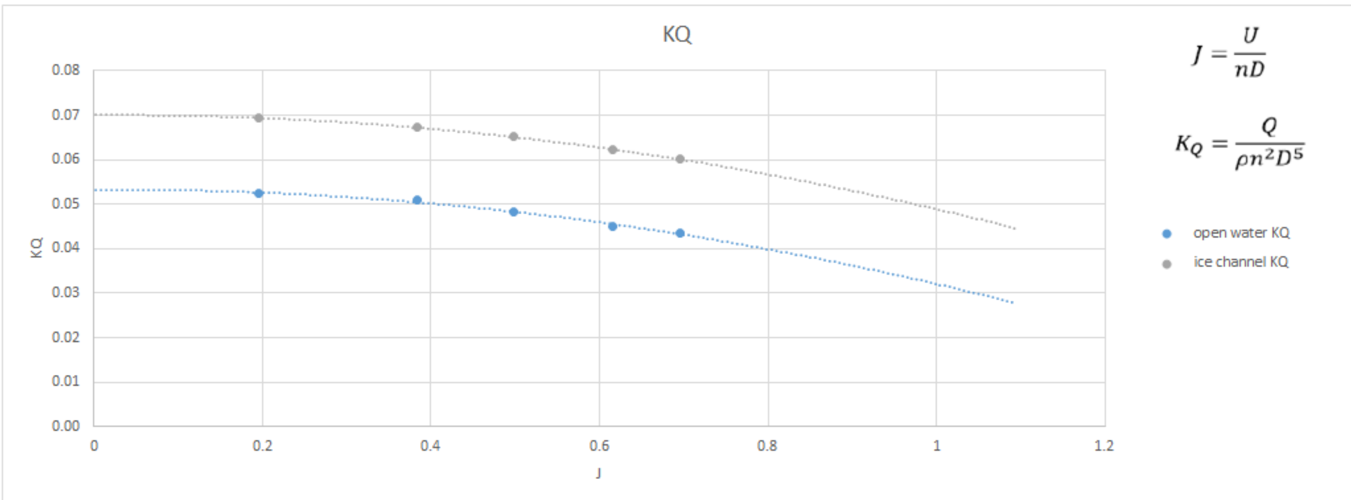

Figure 10. Aranda propeller KQ curve for open water and ice conditions.

3. Aranda shaft line model for torsional vibration analysis

To carry out a torsional vibration analysis of a shaft line all significant parts of the shaft line have to be modelled with good accuracy. Thus, this requires detailed knowledge of the shaft line components. Figure 11. shows the ducted propeller of R/V Aranda. Figure 12 shows the original shafting arrangement where the dimensions and other information about the shaft line components can be seen. During the modernization of R/V Aranda only the motor side of the shaft line was modified.

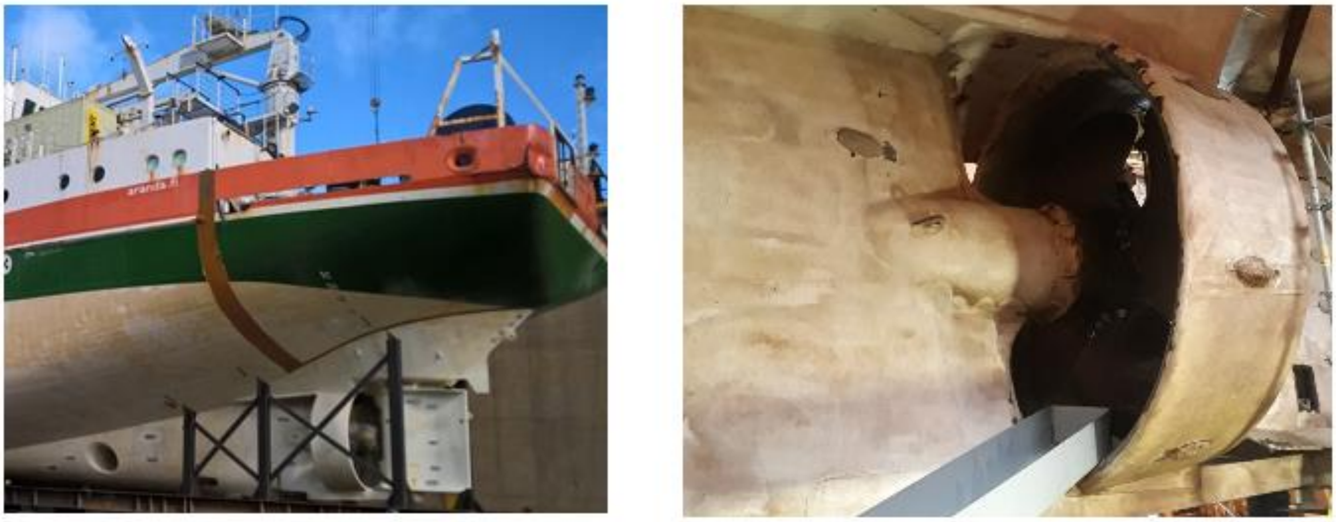

Figure 11. Ducted propeller of R/V Aranda (photo courtesy of SYKE)

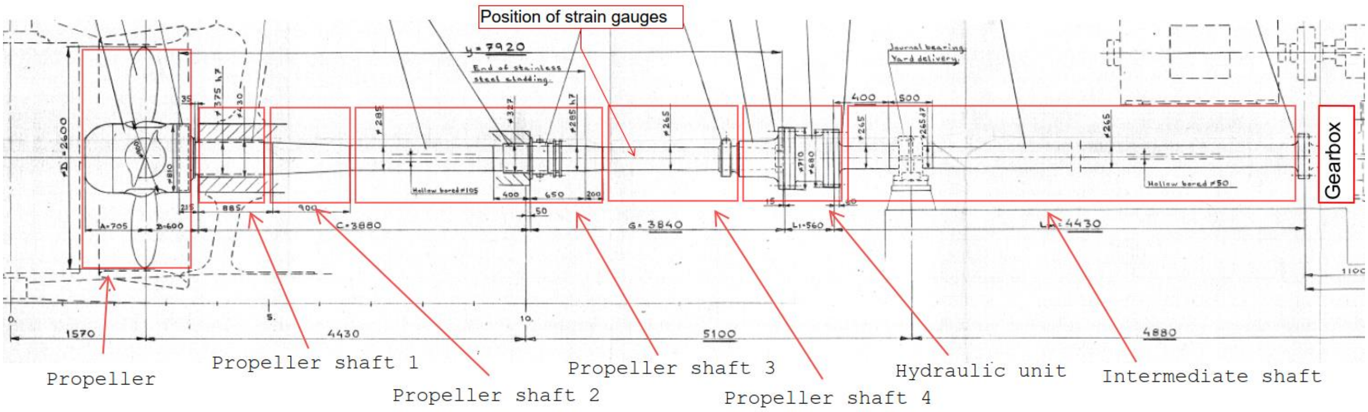

Figure 12. Original shafting arrangement of R/V Aranda with comments, see table for details. New gearbox and flexible couplings not shown.

Because the propeller shaft had different diameters along the shaft length, it was modelled in parts. Inertia, torsional stiffness and damping values for the shafts were calculated from the geometry given in Figure 12. The propeller inertia was taken from the shafting arrangement drawing where the inertia with water added mass was given. Values for the flexible coupling were taken from the manufacturer’s datasheet (Vulcan Rator G2D1H). Gearbox is modelled as ideal and only has the gear ratio parameter. Some of the data was taken from the TVA analysis report performed by the Shipyard. Table 1. sums up the values used in the simulation.

Table 1. Shaft line data for torsional vibration analysis

Component	Inertia [kgm^2]	Stiffness [kNm/rad]	Damping [Nms/rad]
Propeller, hub, flange	1445	-	KQ curve
Propeller shaft 1	13.3	171 000	954
Propeller shaft 2	8.4	114 000	619
Propeller shaft 3	14.1	56 700	562
Propeller shaft 4	11.4	42 100	438
Hydraulic unit	74	-	
Intermediate shaft	30.2	8 620	322
Flexible coupling Vulcan Rator	9.9	261	3633
Electric motor	116	-	100

For the propeller torque the KQ curve developed in chapter *2.4* was used. This also takes into account the damping of the propeller.

It should be noted that R/V Aranda has two electric propulsion motors which are linked together with the reduction gearbox. There are also two flexible couplings (between the motor and gearbox). In the simulation model these are modelled with only one motor and one flexible coupling. However, the values are taken as double to have the correct inertia etc. This simplification should not greatly affect the simulation results.

The simulation is carried out with Matlab Simulink (Simscape) in time domain. Figure 13. shows the main simulation model.

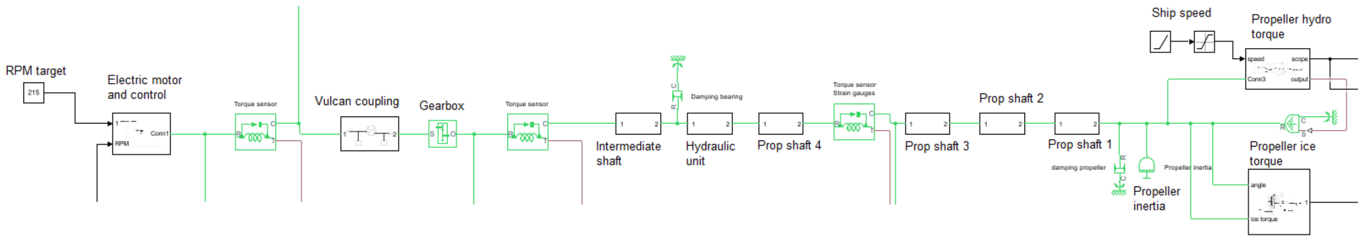

Figure 13. Matlab Simscape model of the Aranda shaft line.

As can be seen in Figure 13, the electric motor is added as a torque source on the motor end of the shaft line and the hydrodynamic torque and ice torque are added as torque sources at the propeller end of the shaft line. The Ice torque is calculated according to FSICR.

3.1 Simulated lowest rotational natural frequency of the shaft line

One simple way to validate the simulation model is to compare the natural frequencies of the shaft line to those measured at the sea trials, see chapter 2.3. Matlab Simscape model does not give out the system nominal frequencies directly, but they can be determined from the simulated timehistory of the torque signal. In simulation a sharp pulse can be used for excitation, as seen in Figure 14. From the response signal, the lowest torsional natural frequency of the shaft line was determined as 9.3 Hz, which is quite well in line with the measurements. This indicates that at least the inertia and stiffness values in the shaft line model are correct.

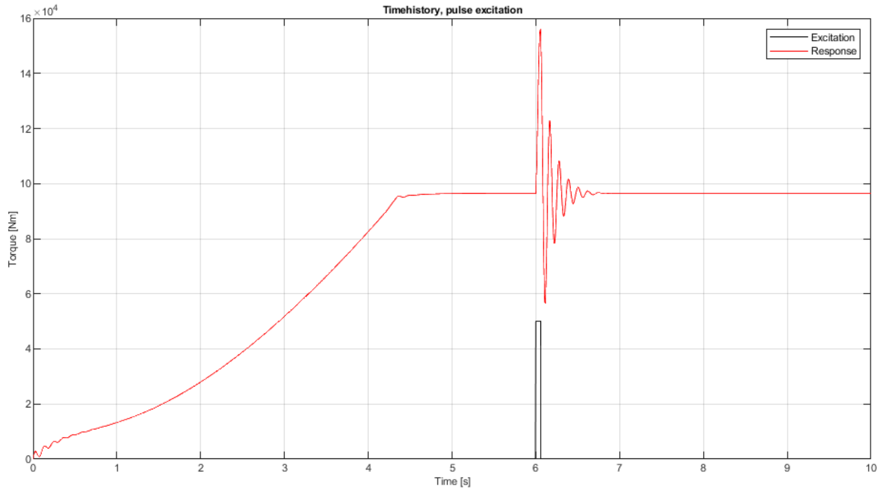

Figure 14. Aranda Shaft line response, pulse excitation.

To have better understanding how the shaft line responds to ice excitation on wide RPM range, simulations were run with different RPM and the ratio between response and excitation torque was investigated. The excitation in this case was ice class IC case 1. Figure 15. shows the results. In frequency range corresponding to propeller RPM 140 (9.3 Hz blade frequency) the resonance area is clearly seen. The ratio between the Q_{res} / Q_{exc} is called dynamic magnification.

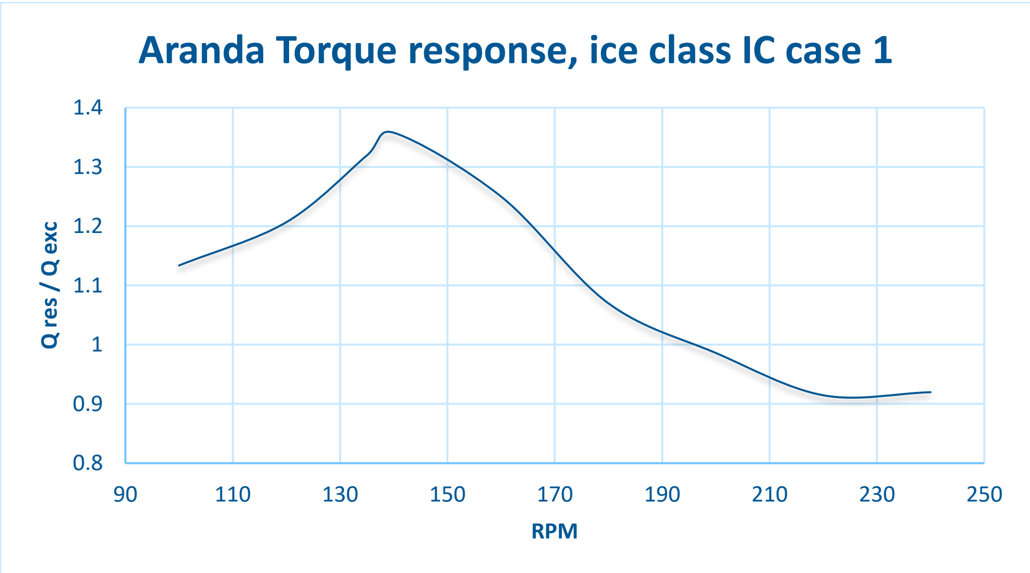

Figure 15. Simulated torque response of the propeller shaft, excitation: ice class IC case 1.

3.2 Engine loading control

The electric motor in the simulation model is modelled with ideal torque source. The input to the ideal torque source is the wanted torque value. However, the application of the torque in this case is instant, which is not realistic and can cause problems in the model. Also, in case of increased torque demand the electric motor is able to respond with overtorque, which is important in propeller ice milling situation. Usually at least 25 % overtorque is possible.

For more realistic torque control, a simple control scheme with Simulink PID block is realised in the model. Input to the control system is the wanted RPM of the propeller shaft. Thus, the control first runs the propeller to the correct RPM and then when the ice milling sequence starts the control tries to keep the rpm at the ordered level. There is a limitation to the motor input torque so that the 25 % over torque limit is not exceeded during the ice milling sequence.

4. Comparison of measured and calculated loads

Comparison of simulations and measurements are carried out. The comparison cases include different ice class excitation cases (1 - 4 as in Figure 1.)

4.1 R/V Aranda maximum ice torque for different ice classes

Maximum ice torque is calculated as required in the FSICR chapter 6.5.3. Below in Table 2. the parameters for the calculation are shown.

Table 2. Parameters used for ice class torsional calculations

Propeller Hub Diameter, d	0.8	m
Propeller diameter, D	2.6	m
Propeller speed	4.15	revs / s
h ice (IAS = 1.75, IA = 1.5, IB = 1.2, IC = 1)	1.75	m
Propeller type (1 = open, 2 = ducted)	2	
Propeller pitch type (1 = contrl, 2 = fixed)	1	
Transmission type (1 = dir. Diesel, 2 = Electric/Turbine)	2	
Propeller pitch at 0.7, $P_{0.7}$	3.403	
D limit	3.15	m

The resulting maximum ice torque Q_{max} (which is added on top of the hydrodynamic mean torque at nominal operating condition) for each ice class is listed below:

- IAS: 145.7 kNm
- IA: 145.7 kNm
- IB: 118.1 kNm
- IC: 96.6 kNm

The maximum ice torque is the same for IAS and IA classes because the propeller is small when compared to design ice block thickness. According to rules, it is possible to calculate the Q_{max} for different propeller speeds. To simplify the analysis, in the subsequent analysis the Q_{max} is calculated only for the maximum 250 RPM. With 120 RPM the change in this case would be 13 % lower Q_{max}.

Q_{max} is calculated for ducted propeller as is the case with R/V Aranda. For comparison, open propeller maximum Q_{max} torque levels would be 41 % higher.

The ice class also affects the length of the ice milling sequence as described in FSICR chapter 6.5.3.4.1. For IC ice class the sequence length is so short that it actually consists of only ramp up and ramp down.

From the maximum measured torques during the ice trials, as seen in torque distribution charts in Figure 6 and Figure 8, it is evident that the measured torques are much lower than the given maximum FSICR torques in higher ice classes. Thus, the ice conditions have to be taken into account. For IC ice class FSICR gives level ice requirement of 0.4 m ([1] table 4-1), which matches the measured ice thickness during the ice trials quite well. However the given level ice thickness is mainly intended for the hull dimensioning. For the propulsion loads, the ice thickness is given for the ice block size in brash ice channel. As it is considered the most realistic option, the simulations here are mainly carried out for the IC ice class.

Figure 16. shows an example of the simulated results for all ice milling sequences (ice class IC cases 1 - 4, RPM = 215). As can be seen already from the Figure 15. the dynamic magnification at 215 RPM is low, which is also visible here. The highest response is achieved in case 2 which is more static case without dynamic behaviour. The higher frequency case 3 (twice the blade frequency) does not seem to excite the shaft at this RPM.

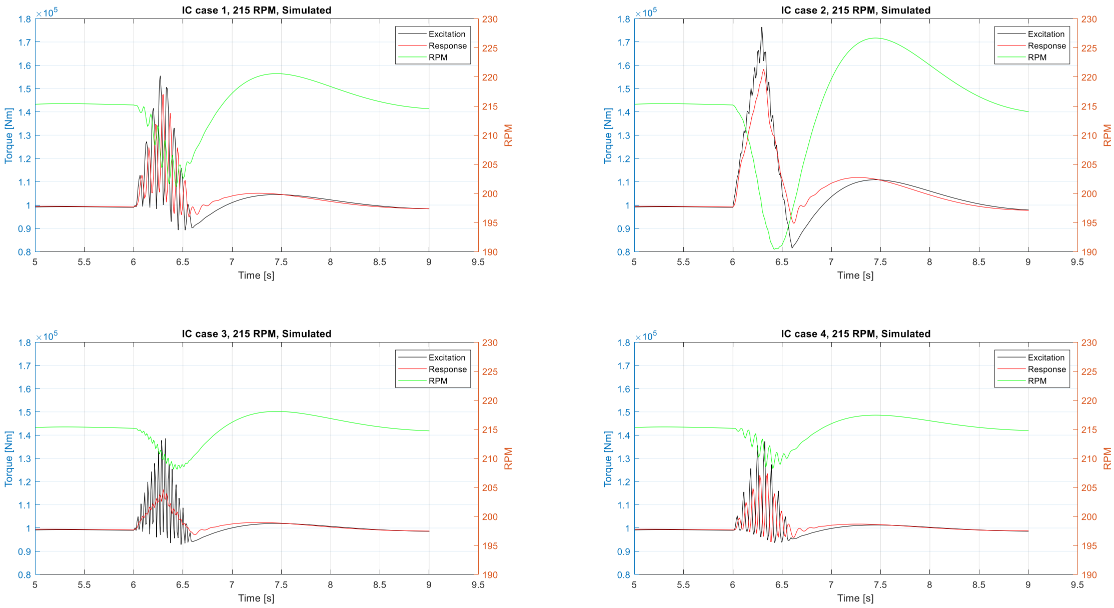

Figure 16. Simulated cases with excitation, response and RPM. Ice class IC, cases 1 - 4. Initial RPM = 215.

4.2 Comparison of simulated and measured torque levels

below the simulated results are compared to measurements for chosen cases. The first two cases in chapters 4.2.1 and 4.2.2 are the maximum measured torque peaks during the transit voyages in ice channel. Because the two transit voyages were run with different RPM levels it is interesting to compare them to the simulations. As already discussed in chapter 2.2 the voyage 1, run with lower RPM and lower power level, had the higher torque peaks (peaks around the mean torque). The third case in chapter 4.2.3 is a reversing case in ice channel where the highest torque levels during the whole ice trials were measured.

4.2.1 Voyage 1, ice channel, 9.7 kn, 176 RPM

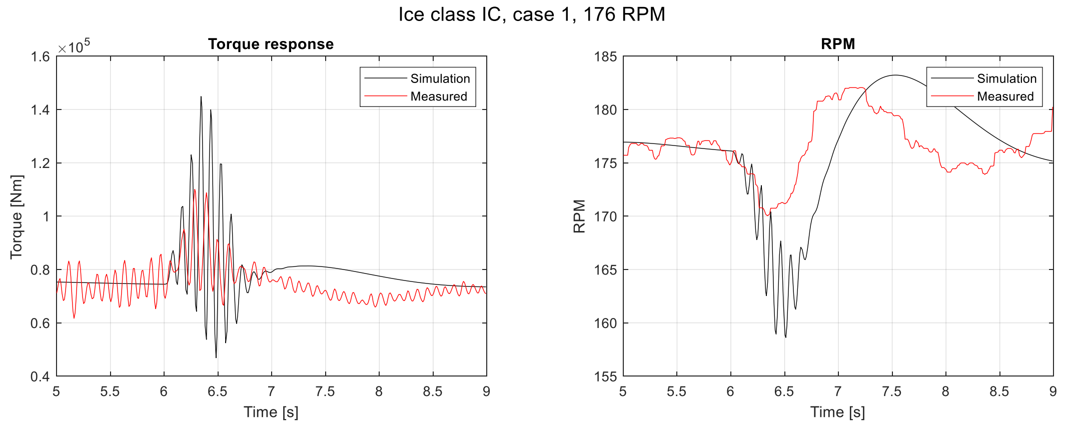

Figure 17. Voyage 1, comparison of highest measured torque to simulated ice class IC case 1.

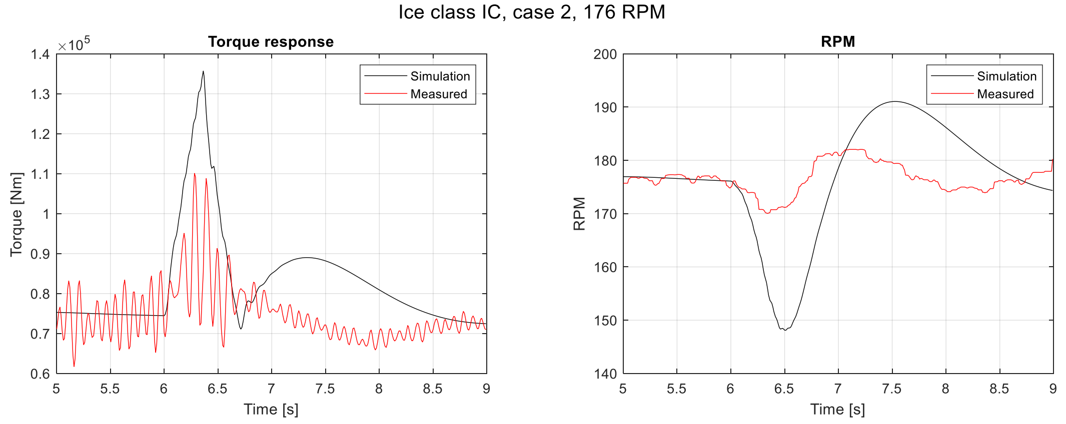

Figure 18. Voyage 1, comparison of highest measured torque to simulated ice class IC case 2.

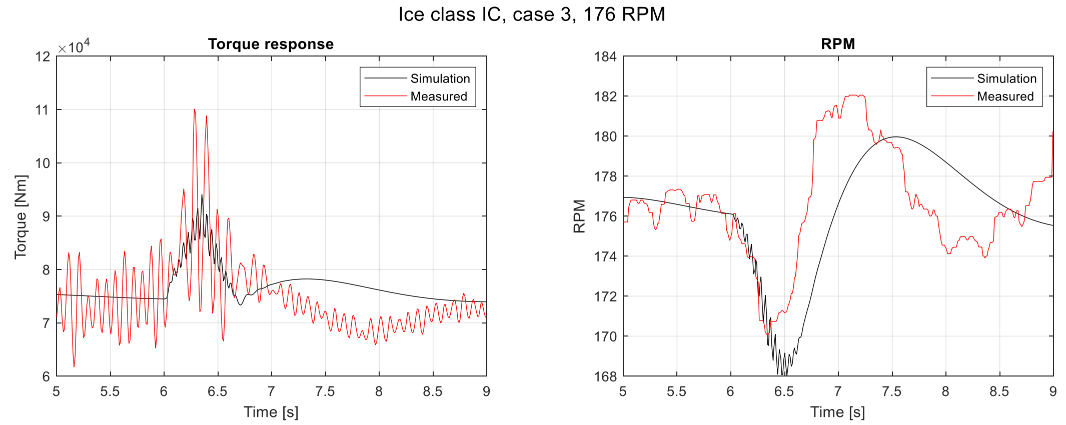

Figure 19. Voyage 1, comparison of highest measured torque to simulated ice class IC case 3.

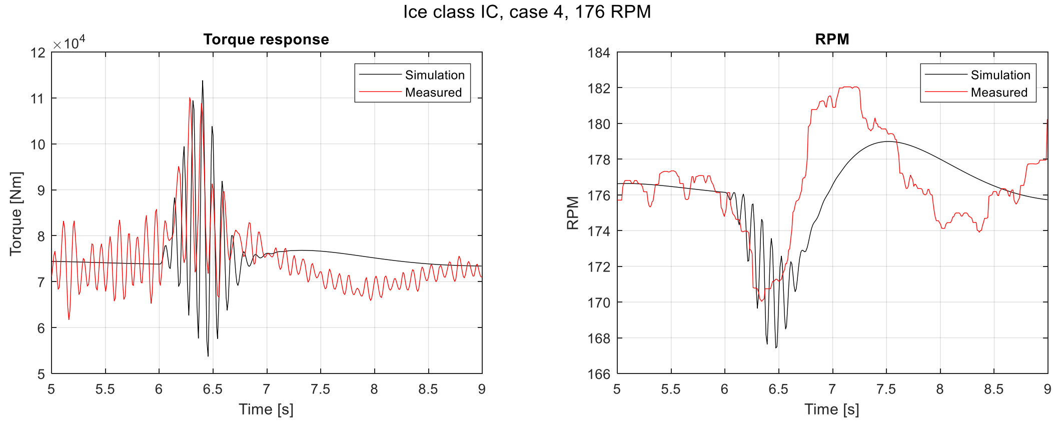

Figure 20. Voyage 1, comparison of highest measured torque to simulated ice class IC case 4.

4.2.2 Voyage 2, ice channel, 10.5 kn, 215 RPM

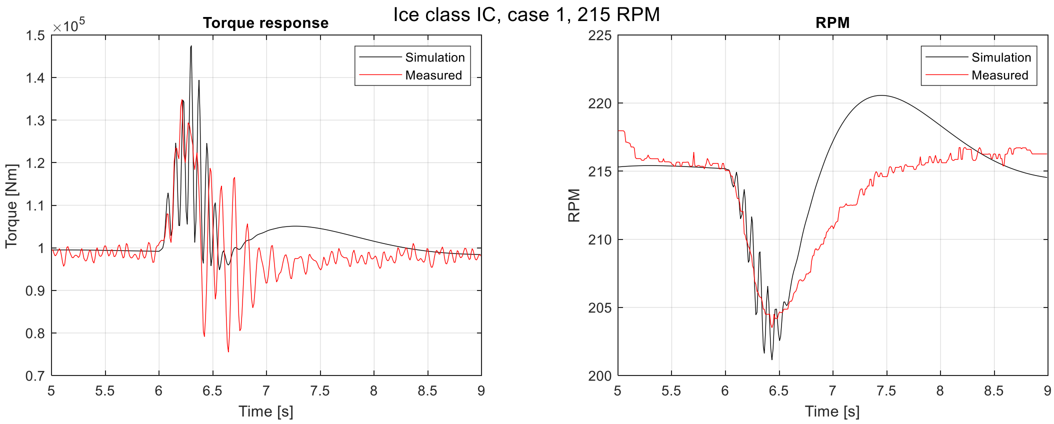

Figure 21. Voyage 2, comparison of highest measured torque to simulated ice class IC case 1.

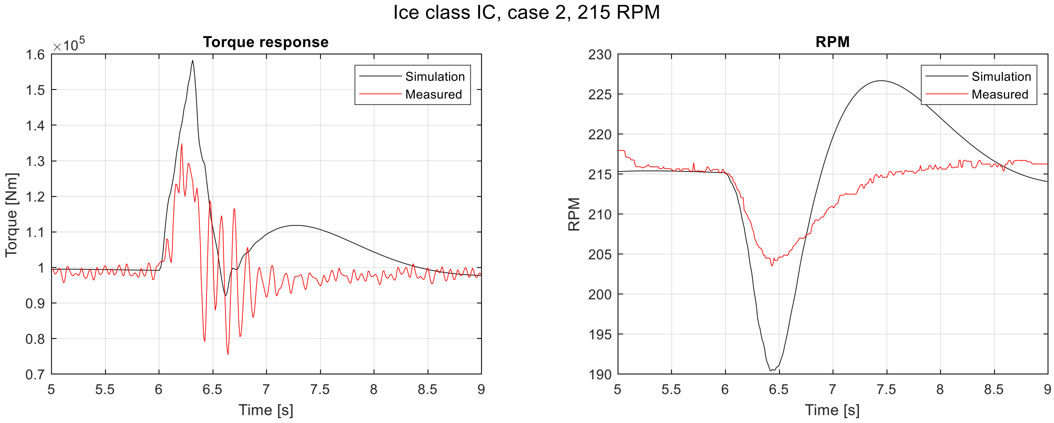

Figure 22. Voyage 2, comparison of highest measured torque to simulated ice class IC case 2.

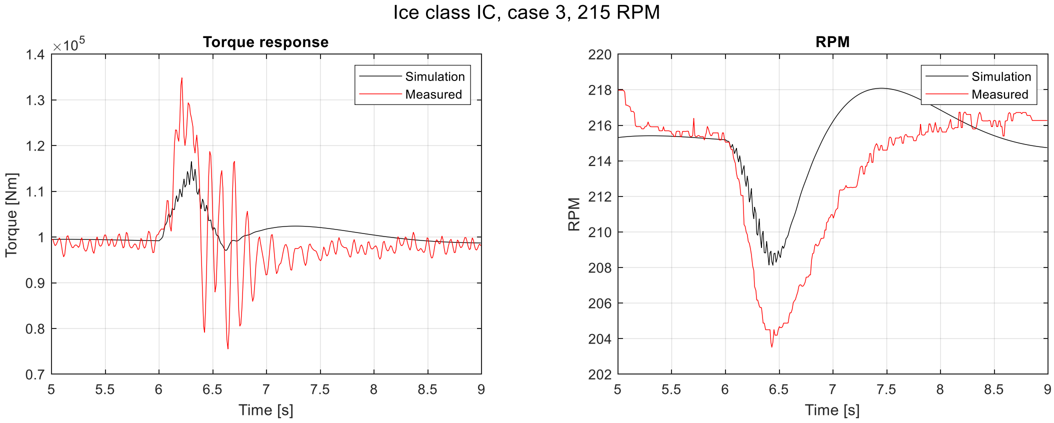

Figure 23. Voyage 2, comparison of highest measured torque to simulated ice class IC case 3.

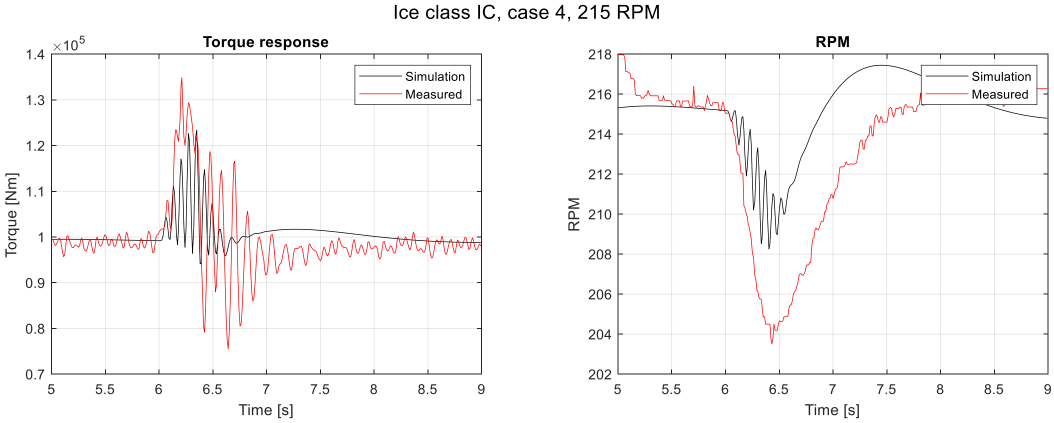

Figure 24. Voyage 2, comparison of highest measured torque to simulated ice class IC case 4.

4.2.3 Reversing test in ice channel, 3.7 kn, 169 RPM

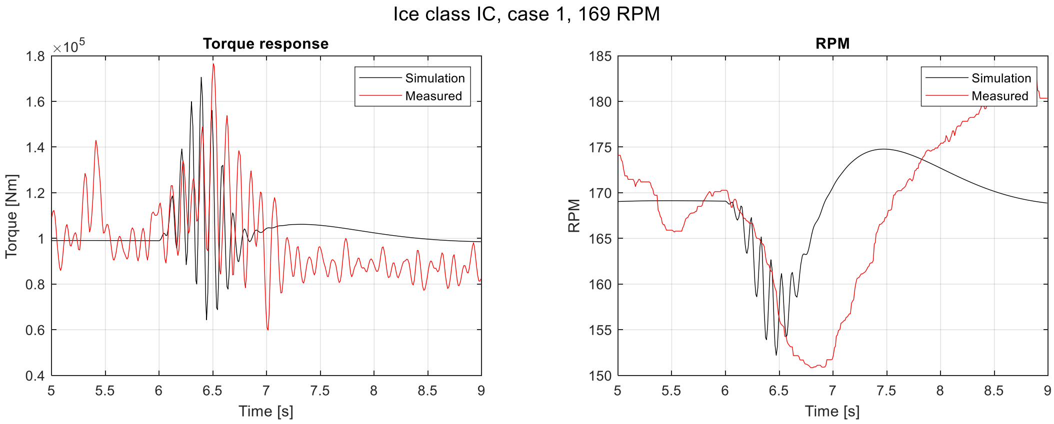

Figure 25. Reversing test, comparison of highest measured torque to simulated ice class IC case 1.

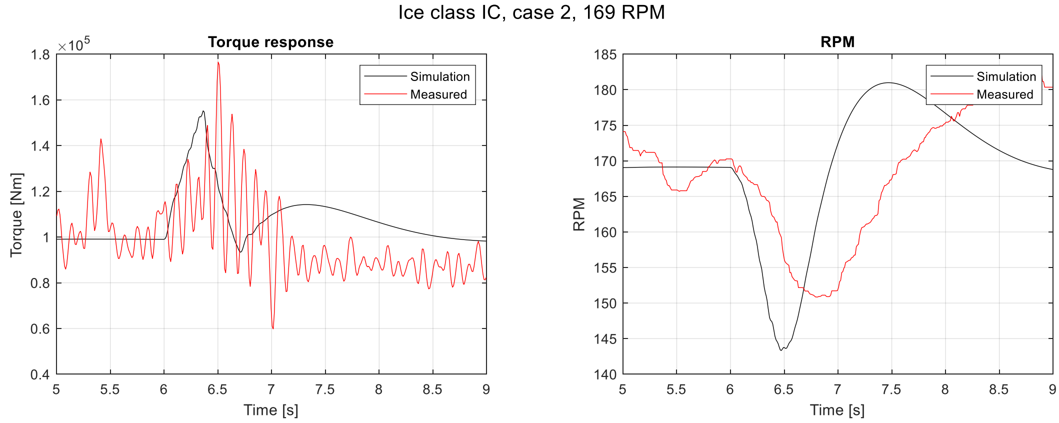

Figure 26. Reversing test, comparison of highest measured torque to simulated ice class IC case 2.

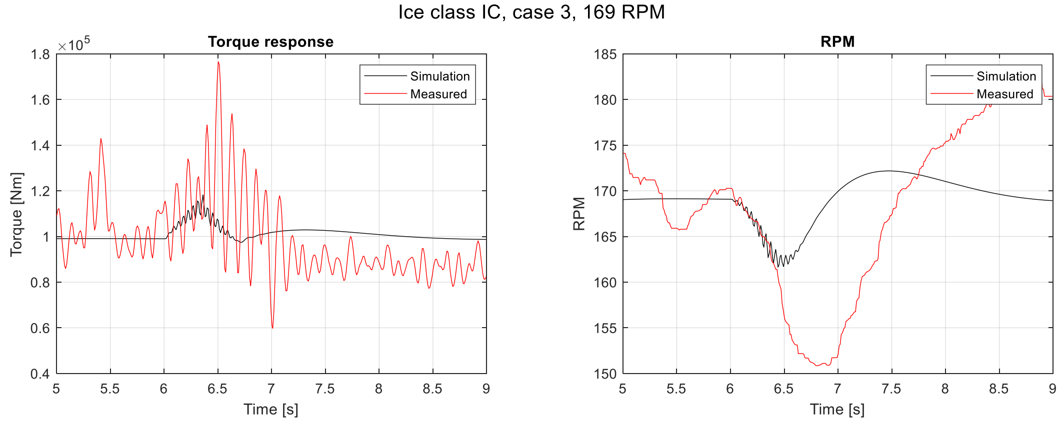

Figure 27. Reversing test, comparison of highest measured torque to simulated ice class IC case 3.

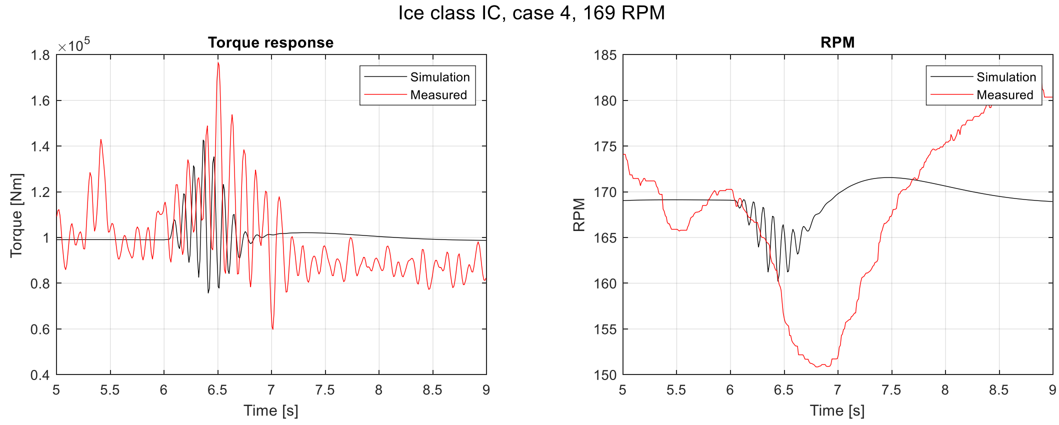

Figure 28. Reversing test, comparison of highest measured torque to simulated ice class IC case 4.

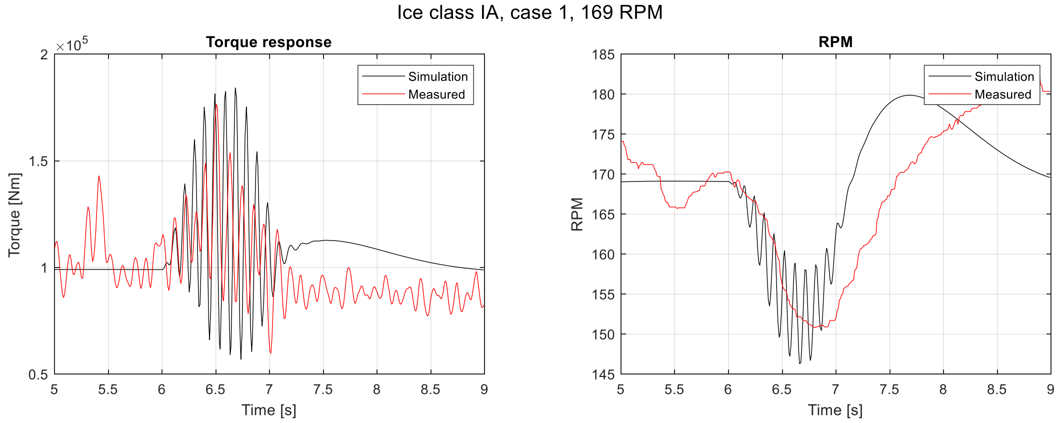

Figure 29. Reversing test, comparison of highest measured torque to simulated ice class IA case 1.

4.2.4 Analysis of comparison between measured and simulated torque response

By visually inspecting the results from voyage 1 (Figure 17. - Figure 20.), it seems that the ice milling sequence in case 4 offers a quite good match with the measured data. Also, in case 4, the RPM drop is well in line with the measurements. Case 1 simulation predicts a much higher torque response, which is not visible in the measurements. Cases 2 and 3 do not match the measured sequence very well. It should be reminded here that it is not known what the real milling sequence at the propeller is, only the response is visible in the measurements. As stated earlier the ice milling cases from the measurements are chosen as they are the maximum cases.

In voyage 2 the simulated case 1 (Figure 21.) is well in line with the measurements, and also se simulated RPM drop is similar than in the measurements. The ice milling sequence chosen from the measured voyage 2 torque timehistory (again the maximum torque case) seems to be a bit longer than the ice class IC ice milling sequence. As already seen in Figure 16, with same simulation parameters, the case 2 gives the highest simulated response. Again, this is because there is not much dynamic magnification at 215 RPM, and thus the case 1 does not excite the shaft as much as seen in voyage 1 simulations with lower RPM.

Finally, the reversing tests in ice channel reveal that the measured torque values are higher than any of the simulated cases with ice class IC, and that the measured ice milling sequence is longer than the simulated one (Figure 25. - Figure 28). The reversing tests were carried out with 169 RPM which is quite close to the resonance area and where the dynamic magnification is already quite high. However, the measured values are much higher than what was measured with almost the same RPM in voyage 1. Thus, it is evident that at least with this ship configuration (shape of the ship aft, rudder arrangement and shape of the nozzle) in reversing mode the ice impacts on the propeller are more severe than in ice channel. It might be that the nozzle has been completely blocked at times during the reversing, which could give rise to added hydrodynamic forces as well. Finally, a simulation was carried out also with higher ice class IA case 1 excitation, and this seem to predict the measured levels better. Also, the longer length of the IA milling sequence is a better fit to the measured one.

In Table 3 the maximum values from Figure 17 - Figure 29 are gathered for an overview.

Table 3. Maximum torque response from measurements and simulations

MAX RESPONSE TORQUE [KNM]						
	Measured	Simulated				
		IC case 1	IC case 2	IC case 3	IC case 4	IA case 1
VOYAGE 1, 176 RPM	109	145	136	93	114	
VOYAGE 2, 215 RPM	135	147	158	117	123	
REVERSING, 169 RPM	176	171	155	117	143	184

4.3 Ice milling sequences

This chapter offers a quick look at the different ice milling sequences (Figure 1.) presented in the rules, and how they compare to ice milling events seen in measurements. Obviously, there are hundreds of milling events in the measurement data, so here only a couple of interesting ones are investigated.
For clarification, the given ice milling cases in the FSICR are the *excitation* loads on the propeller. As stated before, the ice milling excitation on the propeller cannot be directly measured from the shaft with strain gauges, because the strain gauges see the *response* torque, which is a consequence of the shaft line dynamic behaviour. However, with the simulation model it is possible to compare the measured response and the simulated response, and thus link the real excitation to the given rule excitation. This method of course rely on the model capturing the dynamic behaviour of the shaft line correctly.

In general, the excitation case 1 represents a normal situation where one ice block is milled by the propeller. Thus, the torque spikes due to propeller blade hitting the ice block are in blade order frequency. Case 2 represent an event where one ice block is present but the contact time is longer than in case 1 (90 deg vs 135 deg) and the spikes are kind of merged together. In case 3 it is assumed that there are two ice blocks in contact with the propeller blades and thus the torque spikes are with twice the blade order frequency. Case 4 is again with one ice block but with shorter contact time (45 deg) and thus the spikes are sharper than in case 1, but with the same blade order frequency. For all excitation cases there is a 360 degree ramp in which time the torque is raised to the maximum value. At the end of the sequence there is similar ramp down from the maximum value.

From the measurements is seems that the case 1 and case 4 type milling events are frequent. Case 2 events are not so frequent but can be found also. In case 3 type events the response, at least in this case, seems quite similar than in case 2, only with lower amplitude. Figure 30. shows couple of examples.

One noticeable feature of the measured milling sequences is the max torque value is often achieved with the first or the second blade impact, indicating that there might not be much ramp present in these cases.

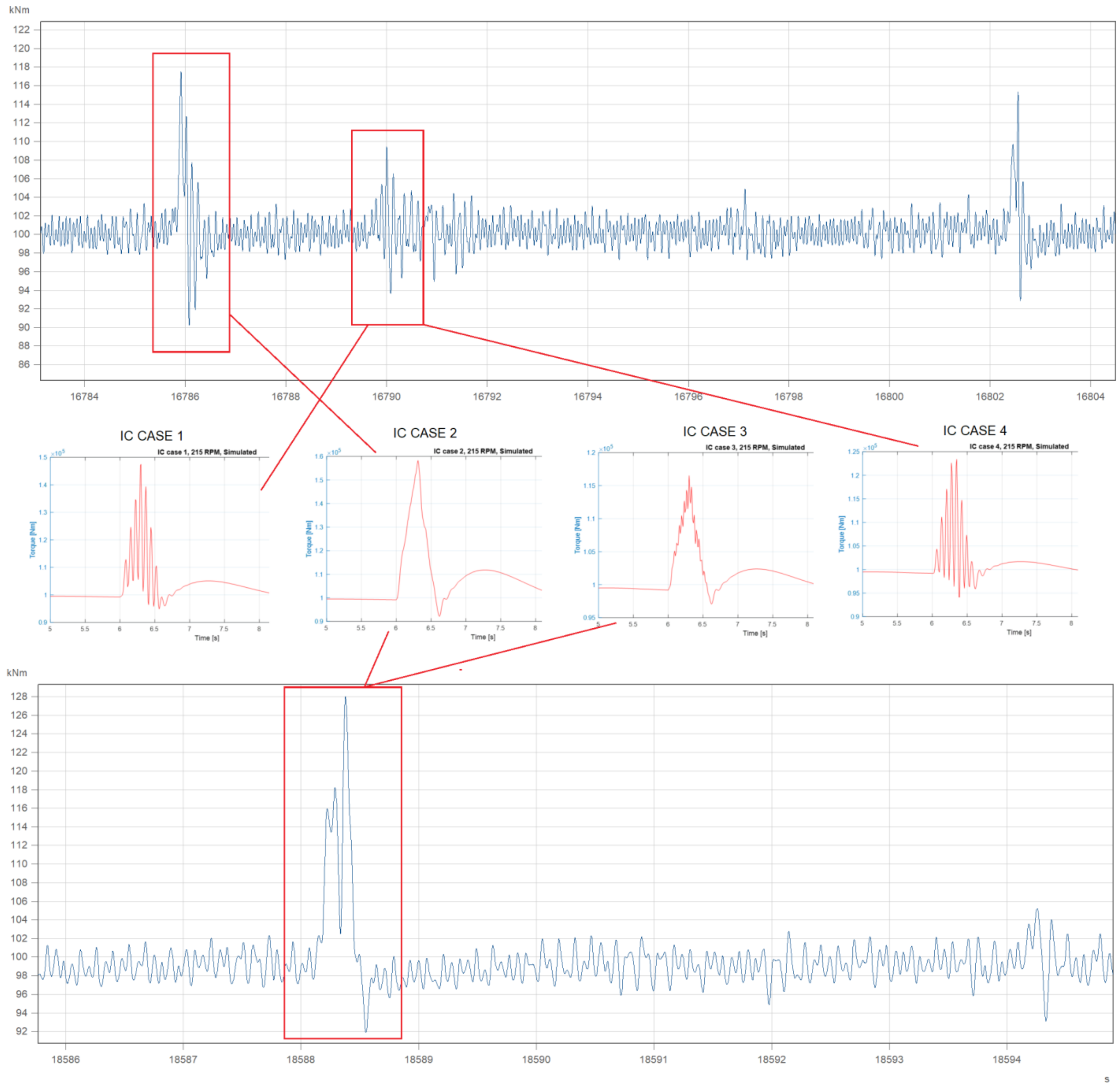

Figure 30. Examples of ice milling sequences from measurements. In the middle the different response patterns for excitation cases 1 - 4 can be seen.

5. Discussion

From results presented in chapter 4, it can be said that the maximum simulated loads are higher than measured ones in normal ice channel operation. The highest measured torque was 15 % lower than highest simulated one. As the lowest ice class IC was used for the simulations, this presents the lowest rule loads. The matching of the ice conditions to the used ice class was done with the level ice thickness. However, this is not exact as there are variations in ice conditions and ice channel characteristics during the voyages. Still, it can be said that the simulated torque levels are quite well in line with the measured ones. Also the RPM drop was quite well captured in the simulations when the torque pattern coincided with the measured one. The correct RPM drop can be important in stalling analysis of directly coupled diesel engines.

The reversing tests in ice channel produced much higher torque levels than what was seen in normal ice channel operation. Also the simulated maximum response torque levels were slightly lower than the measured ones for IC ice class. When the IA ice class excitation was used the simulated torque was quite well in line with the measured one.

Lastly it should be noted that the measurements presented here cover only about four hours of ice channel operations, which might not be sufficient to capture the highest loads. Longer measurements on-board R/V Aranda are hopefully possible in the future.

6. Summary

R/V Aranda performed ice trials in February of 2020. On-board Measurements included torque measurements on the propeller shaft. In this study these measurements are compared to simulated torque response when using the ice milling excitation as given in current Finnish Swedish ice class rules.

The model to simulate the shaft line torsional vibrations was build in Matlab Simscape where time domain simulation can be carried out. Technical drawings and previous analysis by the shipyard were used as input to the model creation.

For ice torque excitation ice class IC was used, as this matched with the mild ice conditions of the ice trials. R/V Aranda has an ice class IA. The comparison data from measurements was chosen from as the maximum torques during the outbound and return voyages in ice channel. These two voyages were run with different speed, power and rpm settings so they offered two different comparison cases. In addition the reversing test in ice channel was also simulated as this had the highest torque levels of all measurements.

Comparison shows that the measured and simulated torque responses during the ice channel voyages are quite similar, with simulation giving slightly higher torque levels. In the reversing tests the measured torque levels were higher than the simulated ones for IC class. For IA ice class the results were quite comparable.

In conclusion, it can be said that the simulated and measured levels, when taking into account the ice conditions, in case of R/V Aranda are quite similar. Thus, the rule load matches the given ice conditions well. It also seems that the 41 % lower ice torque for ducted propeller is in this case justified. However, the torque during reversing tests in ice channel was much higher than in normal forward operation and might be something to study in the future in harsher ice conditions.

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[2] Kannari, P. Full-Scale and Model Tests performed with a nozzle and and Open Propeller simultaneously. IAHR The 9th Ice Symposium 1988, Sapporo, Japan.

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