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**DYNAMIC RESPONSE OF PROPULSION SHAFT LINE SYSTEMS TO PROPELLER
ICE TORQUE EXCITATION**

Finnish Transport Safety Agency

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FOREWORD

In this report no 97, the Winter Navigation Research Board presents part 2 of 2 of the results of the research project GUIDANCE2016. A lumped mass-spring-damper-dashpot model was used to model the vibrational response of three vessels' propulsion shaft lines to the ice torque excitation defined in the Finnish-Swedish ice class rules (FSICR).

The simulated results were compared to results from full-scale measurements in order to determine how well time-domain simulations model the speed drop associated with ice contact. The modelling approach was found to be in general feasible for torque response analysis.

The Winter Navigation Research Board warmly thanks Aki Kinnunen for this report.

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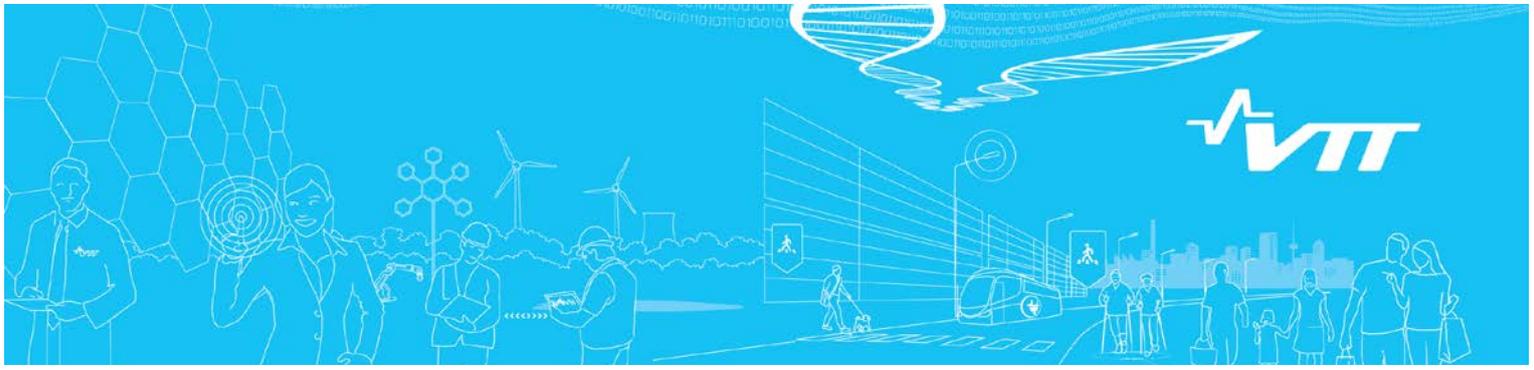
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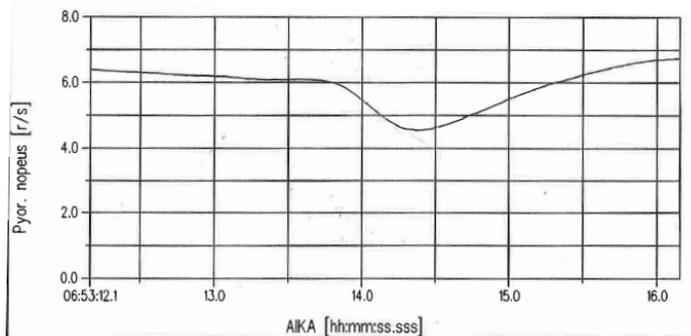
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RESEARCH REPORT

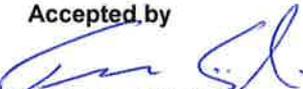
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Dynamic response of propulsion shaft line systems to propeller ice torque excitation

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Summary	
<p>Three vessels' propulsion shaft lines were modelled with lumped mass- spring – damper dashpot method. The method is used commonly in propulsion torsional vibration analysis. The models represent the propulsion shaft system dynamics in the sense that their torsional natural frequencies match with the constructions.</p> <p>The ice torque excitation for propeller was taken from Finnish-Swedish ice class rules, where the torque in ice contact is determined in schematical way. The excitation is scaled per ship propulsion based on the propeller diameter and ice block size. The response calculation was performed with MATLAB® in time domain. The models consisted of common mass, damping and stiffness matrices that were used with excitation parameters for propeller and motor(s).</p> <p>The simulation results based on Finnish-Swedish ice class IA Super excitation were compared with the worst cases found from the measurement. The comparison indicated for M/S Gudingen torque response in simulation was 80% of measured and propeller speed match. For M/ T Sotka torque response in simulation matched measured, propeller speed matched measured. For M/V Akademik Fedorov torque response in simulation match measured, propeller speed drom match measured.</p> <p>For example, in cases of Gudingen and Fedorov, the observed response differs from the simulated in quantitative way – indicating that there is likely more complex excitation mechanism or ice load pattern in reality than is estimated in the ice class rule.</p> <p>The simulated propulsion lines include open propellers. Unfortunately no nozzle propeller vere available for simulations. In general, the modelling approach seems well feasible for torque response analysis.</p>	
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1. Introduction

A task definition with TRAFI / VTT contract for GUIDANGE2016 project says:

IACS group indicates that the ice torque related propeller speed drop indicated in the class-required time domain simulation needs to be checked. Either by experiences from full scale measurements or by collecting information from ship operators / ice breaker masters.

The ice torque related speed drop is simulated in time domain for three vessels and compared to full scale experience. Vessels in this study are M/S Gudingen, M/T Sotka, M/V Akademik Fedorov.

As a background for the study, simulation of speed drop for very large ducted propeller has been compared with measurements by DNV-GL. This comparison revealed that the simulated speed drop was significantly higher what has been measured

2. Goal

The main goal is to check the magnitude of speed drop in simulation versus the full scale experience.

3. Description

The propulsion shafting system dynamic torsional models were constructed in MATLAB® environment and time domain simulations with ice class ice torque excitations were calculated. The response of the system to the ice torque is of interest.

4. Limitations

Three different types of propulsion shaft line systems evaluated:

1. Gudingen with four-stroke diesel, reduction gear and CP propeller
2. Sotka with twin four stroke diesel, 2 in – 1 out gearbox, CP propeller
3. Fedorov with diesel-electric propulsion, FP propeller. Powerplant response not included in the model

All vessels have open propeller, so conclusions are for open propeller propulsion arrangements.

5. Methods

The modelling approach and result types are introduced here. For further details on modelling background see reference [1].

5.1 Dynamic torsional model principle

The torsional models are based on lumped mass – spring – dashpot damping principle. The principle is illustrated in Figure 1.

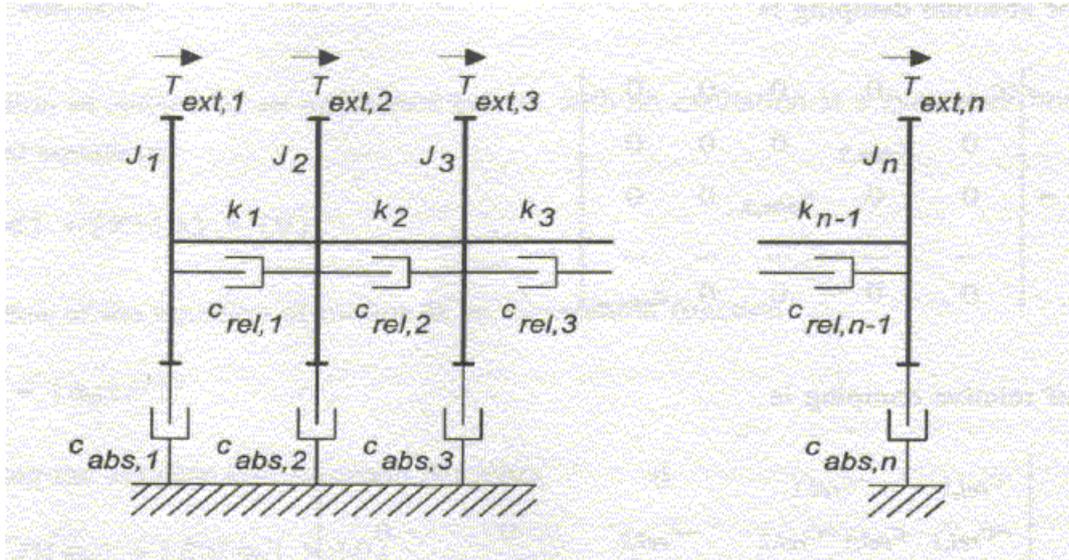


Figure 1. Principle of torsional system dynamic model.

For this kind of system, the equation of motion is expressed as

$$[J]\{\ddot{\varphi}\} + [C]\{\dot{\varphi}\} + [K]\{\varphi\} = \{T_{ext}\}$$

where $[J]$ denotes inertia matrix, $[C]$ is damping matrix and $[K]$ is stiffness matrix. Excitation vector is $\{T_{ext}\}$ and angular displacement is $\{\varphi\}$. This approach is familiar from finite element method and computations in this case follow finite element method principles.

The system excitation is torque from propeller, and is expressed in terms of hydrodynamic torque and ice torque.

$$T_{ext} = T_{hydro} + T_{ice}$$

The ice torque is taken from the latest FSCIR rules draft proposal (2016 August), and is in general following the form in Figure 2.

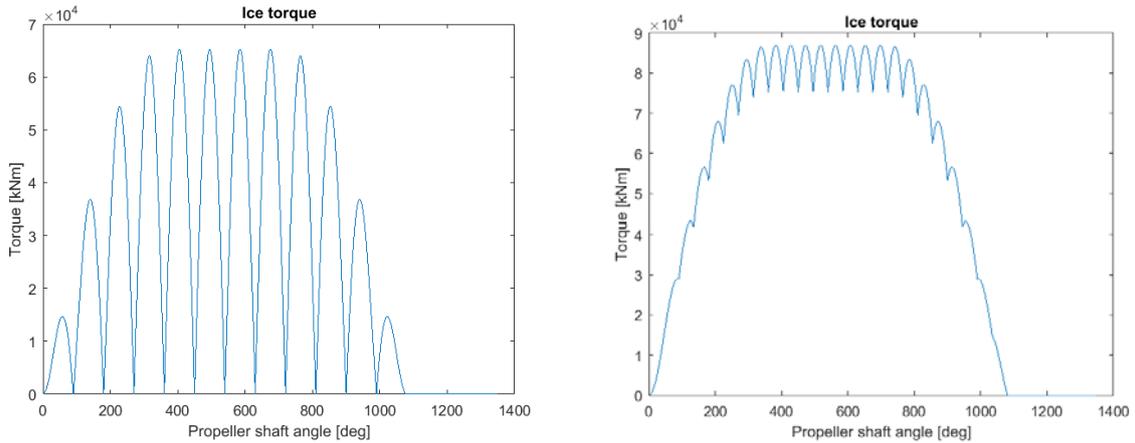


Figure 2. Ice torque excitation typical examples. Excitation case 1 on the left, excitation case 2 on the right, for M/S Gudingen IA Super class.

5.2 Results format

The results of the simulation is a response overall in the model. In the results, the shaft torque response and propeller excitation are shown. Also, the propeller rotating speed is presented. Example is shown in Figure 3.

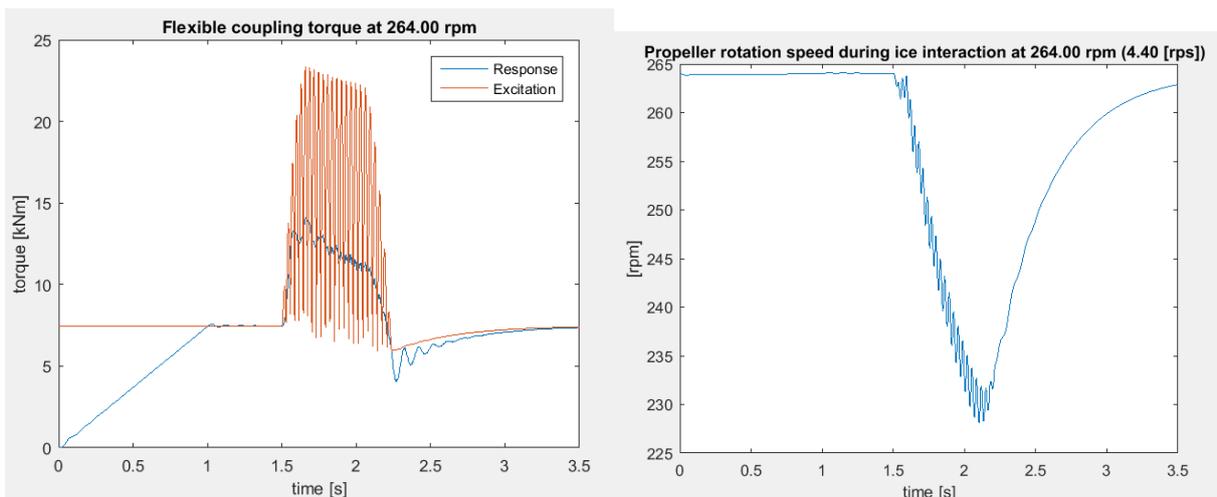


Figure 3. Result example of shaft torque excitation and response on the left. On the right, the rotating speed response of the system.

6. Results

6.1 M/S Gudingen

6.1.1 Comparison case definition

The comparison case for simulation is

- Propeller speed 366 RPM, ice block IA Super, excitation torque in simulation from FSCIR torque excitation case 1 and 3.

6.1.2 Simulation and measurement results

For excitation case 1, the simulated torque excitation and response are shown in Figure 4. The propeller RPM in simulation is presented in Figure 5.

For excitation case 2, the simulated torque excitation and response are shown in Figure 6. The propeller RPM in simulation is presented in Figure 7.

The measurements are in Figure 8. It is obvious that the torque simulation results for excitation case 1 are qualitatively closer to measured. Simulation results for excitation case 2 are qualitatively different than observed in measurement. Therefore, it is more reasonable to compare excitation case 1 and measurement.

Comparison of measurement and simulation is seen in Figure 9 for torque and in Figure 10 for propeller speed.

The simulated torque response is about 80% of measured torque response. Speed drop in simulation matches quite well the measured event.

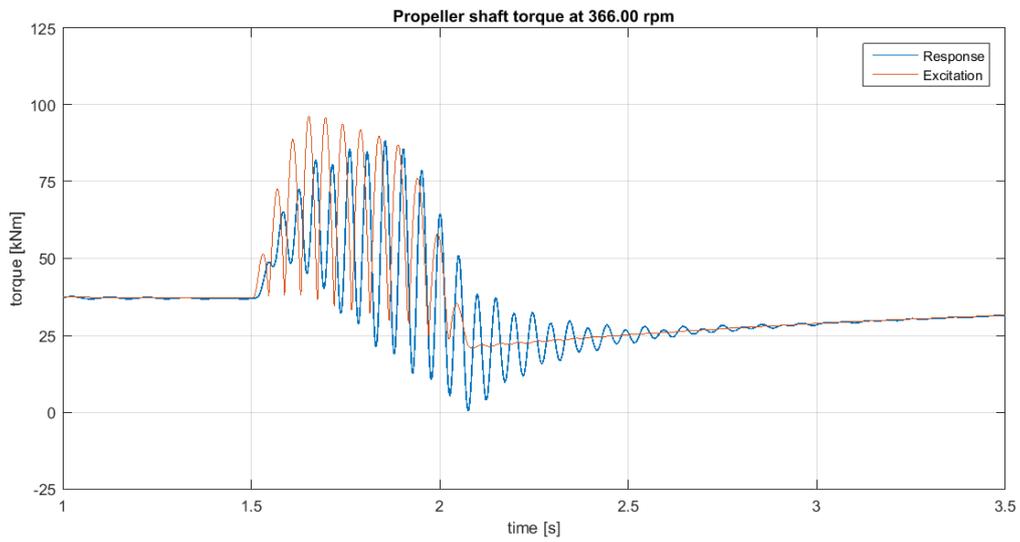


Figure 4. M/S Gudingen ice torque simulation excitation (red) and response (blue). Excitation case 1.

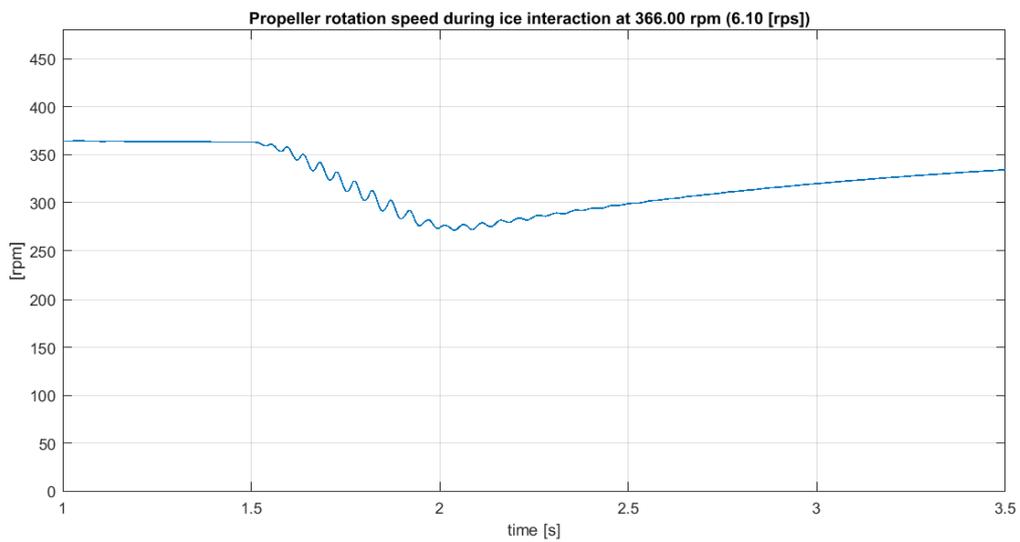


Figure 5. M/S Gudingen, propeller speed in simulation, during ice-interaction. Excitation case 1.

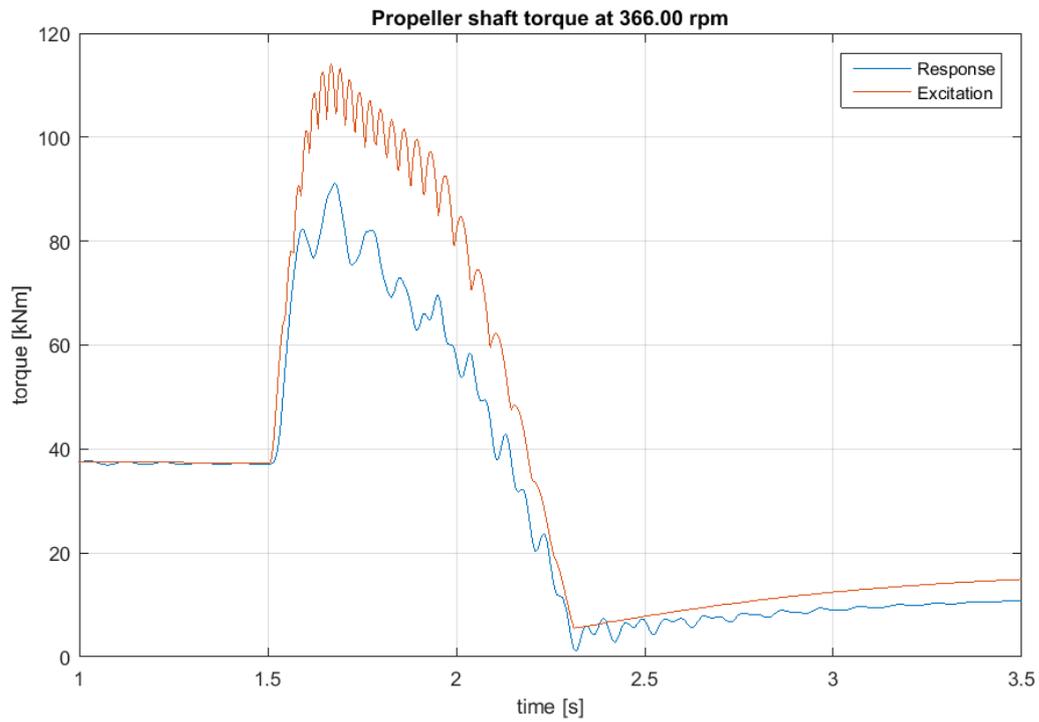


Figure 6. M/S Gudingen ice torque simulation excitation (red) and response (blue). Excitation case 2.

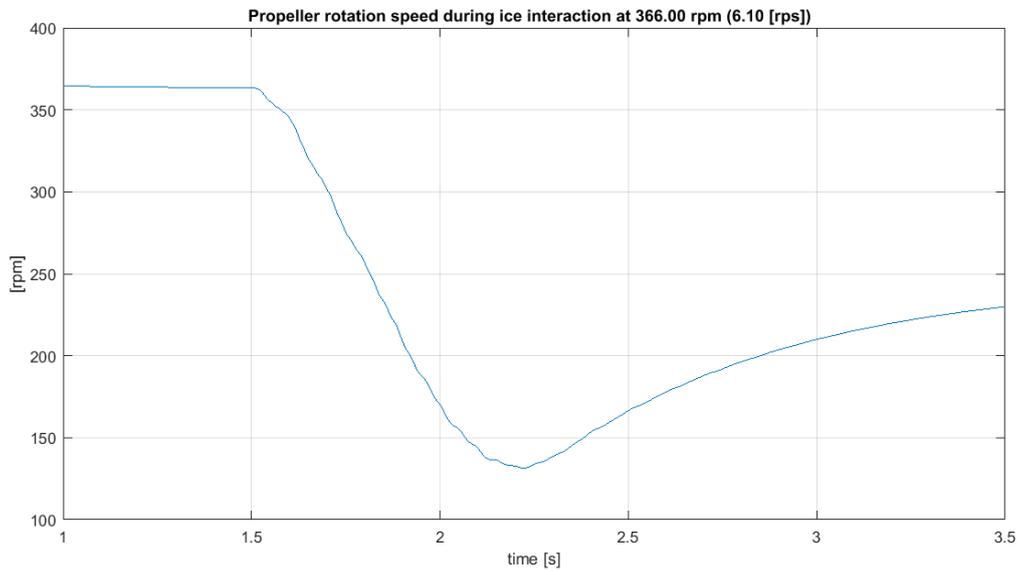


Figure 7. M/S Gudingen, propeller speed in simulation, during ice-interaction. Excitation case 2.

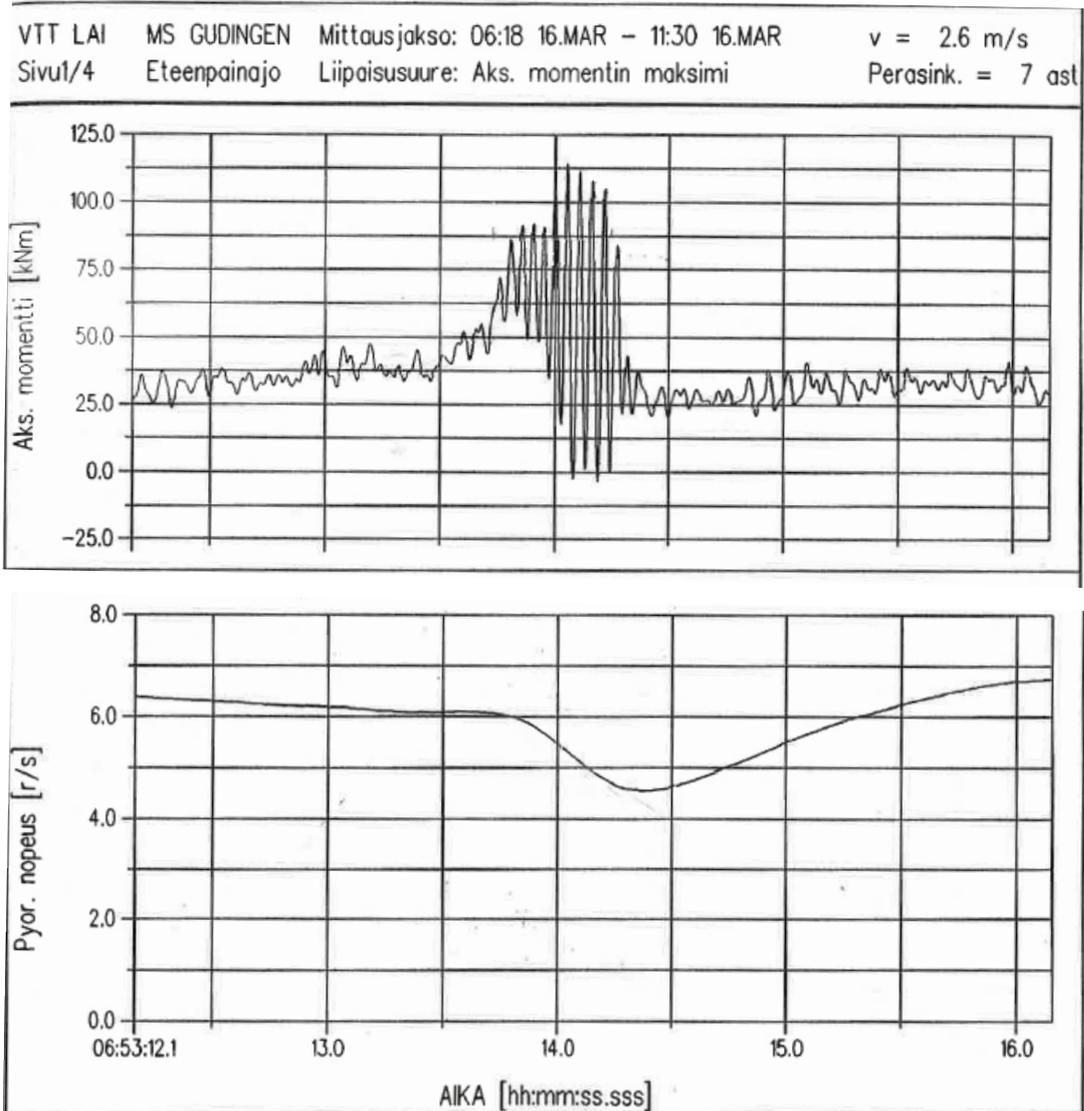


Figure 8. M/S Gudingen, measured propeller shaft torque (top) and propeller rotation speed in rev/second.

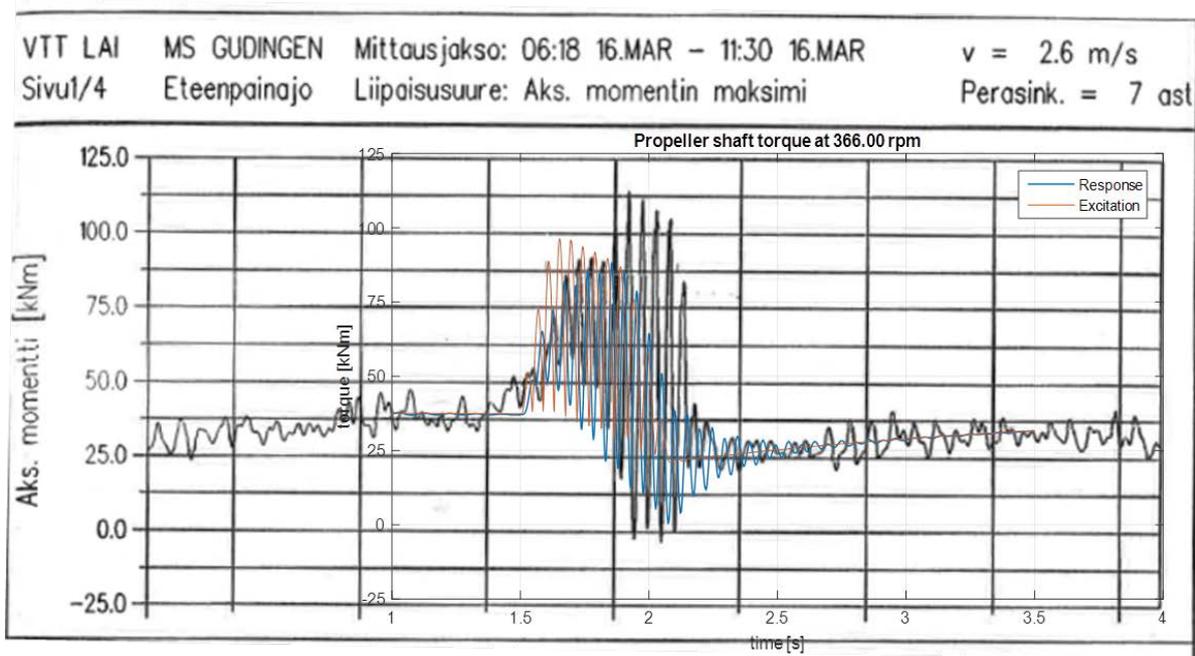


Figure 9. Comparison of simulated and measured torque response of M/s Gudingen

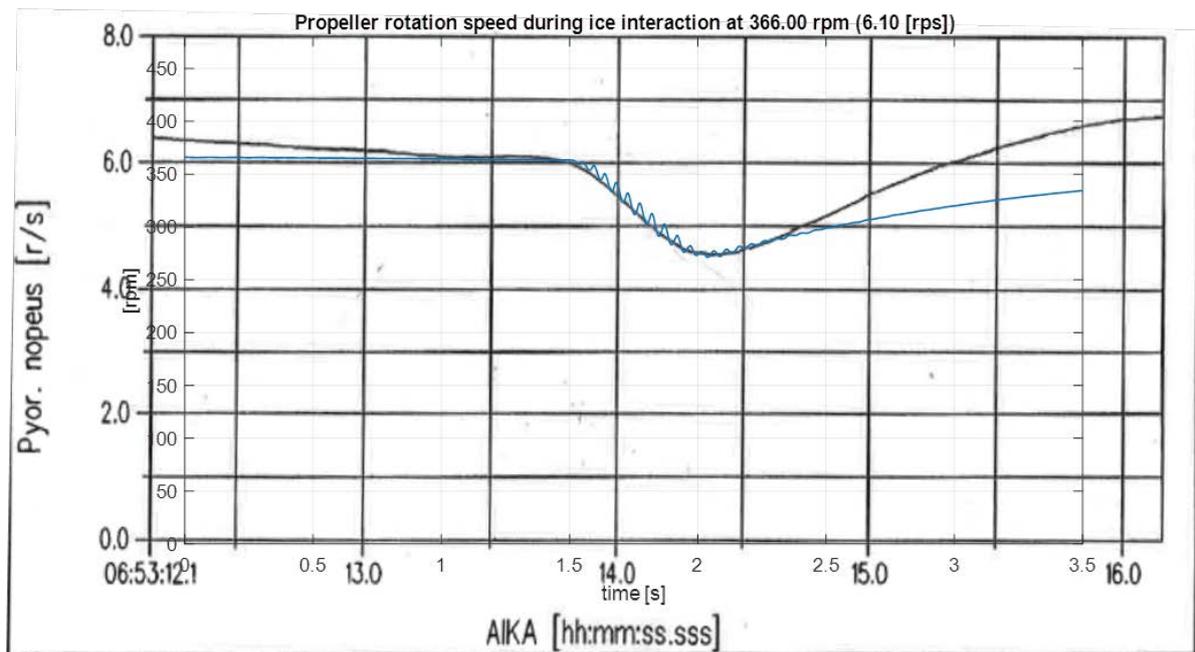


Figure 10. M/S Gudingen propeller RPM during ice interaction, measured and simulated compared.

6.2 M/T Sotka

6.2.1 Comparison case definition

The comparison case for simulation is

- propeller speed 120 RPM
- propeller at 660 kNm hydrodynamic torque level
 - Propeller KQ fitted for the case, to correspond P/D 0.8 in measurement, instead of propeller max P/D 1.07, J-dependency of KQ not used (advance coefficient independent KQ)

6.2.2 Sotka simulation and measurement results

For excitation case 1, the results for simulated ice torque excitation are in Figure 11. Corresponding speed in simulation is shown in Figure 12.

For excitation case 2, the results for simulated ice torque excitation are in Figure 13. Corresponding speed in simulation is shown in Figure 14.

The measurement results are in Figure 15. The ice torque simulation results for excitation case 1 are qualitatively more like the measurement, therefore, it appears to be better to compare simulation of excitation case 1 and measurement.

Comparison of simulation and measurement is in Figure 16. The torque and speed in simulation match the measured figures well.

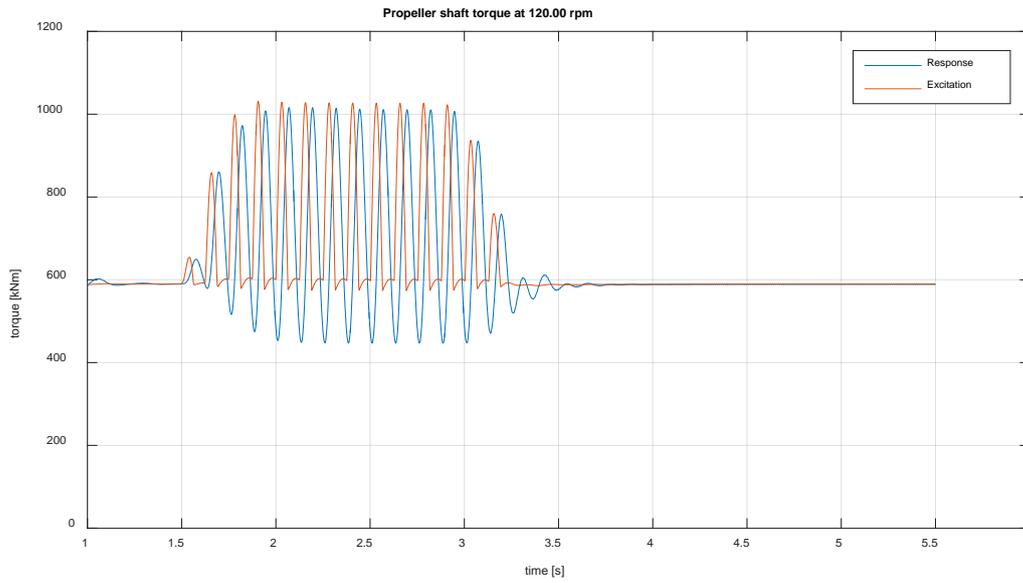


Figure 11. Ice torque on propeller (red) and propeller shaft dynamic response (blue) in ice interaction even, M/T Sotka, excitation case 1.

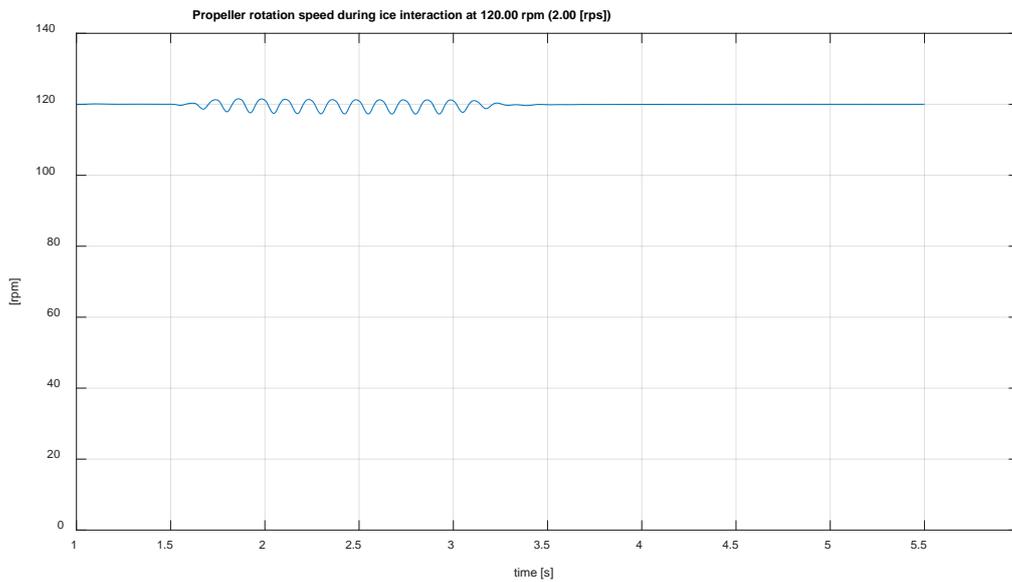


Figure 12. M/T Sotka propeller rotation speed in ice interaction event. RPM drop is small. Excitation case 1.

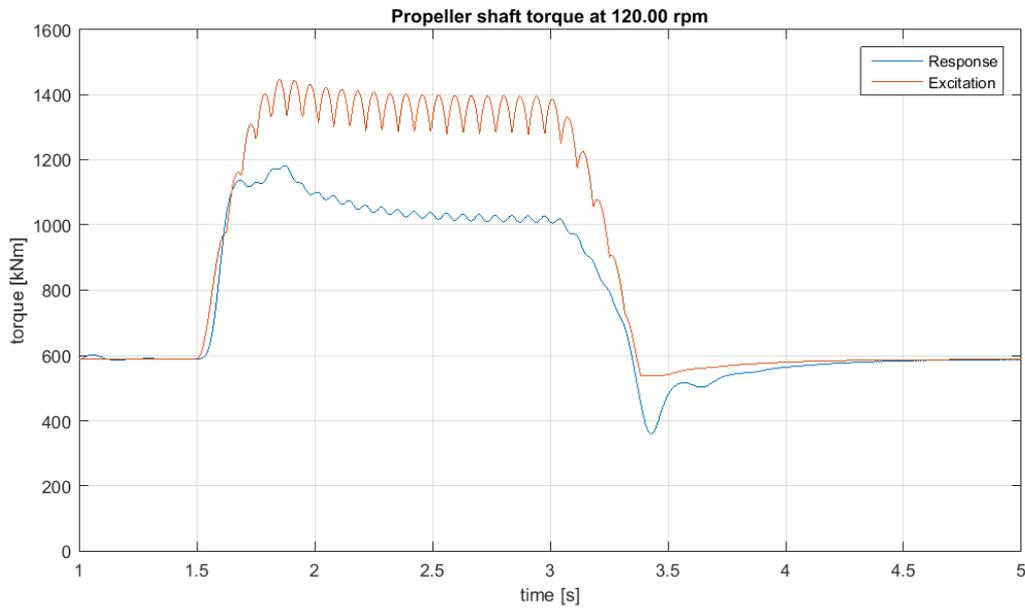


Figure 13. M/T Sotka ice torque simulation excitation (red) and response (blue). Excitation case 2.

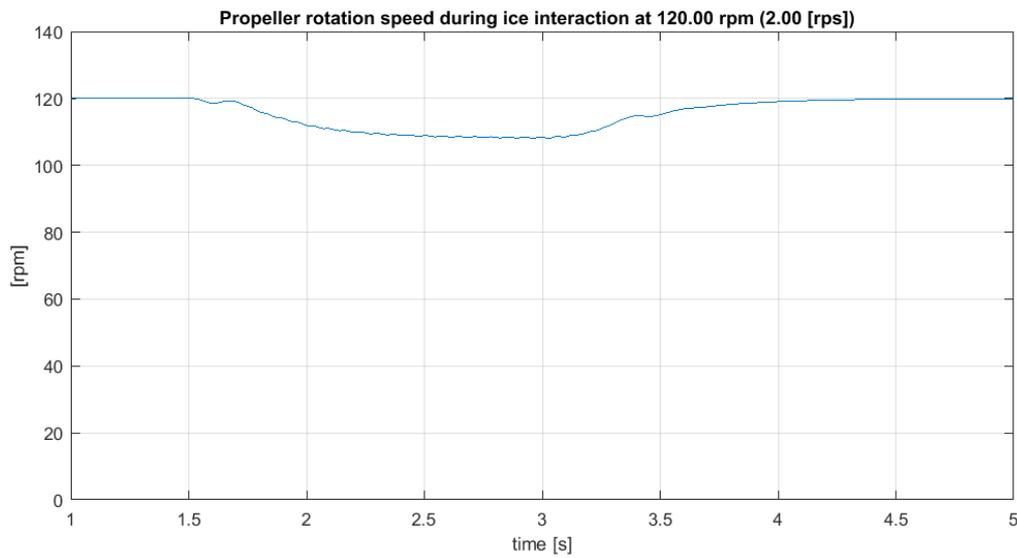


Figure 14. M/T Sotka, propeller speed in simulation, during ice-interaction. Excitation case 2.

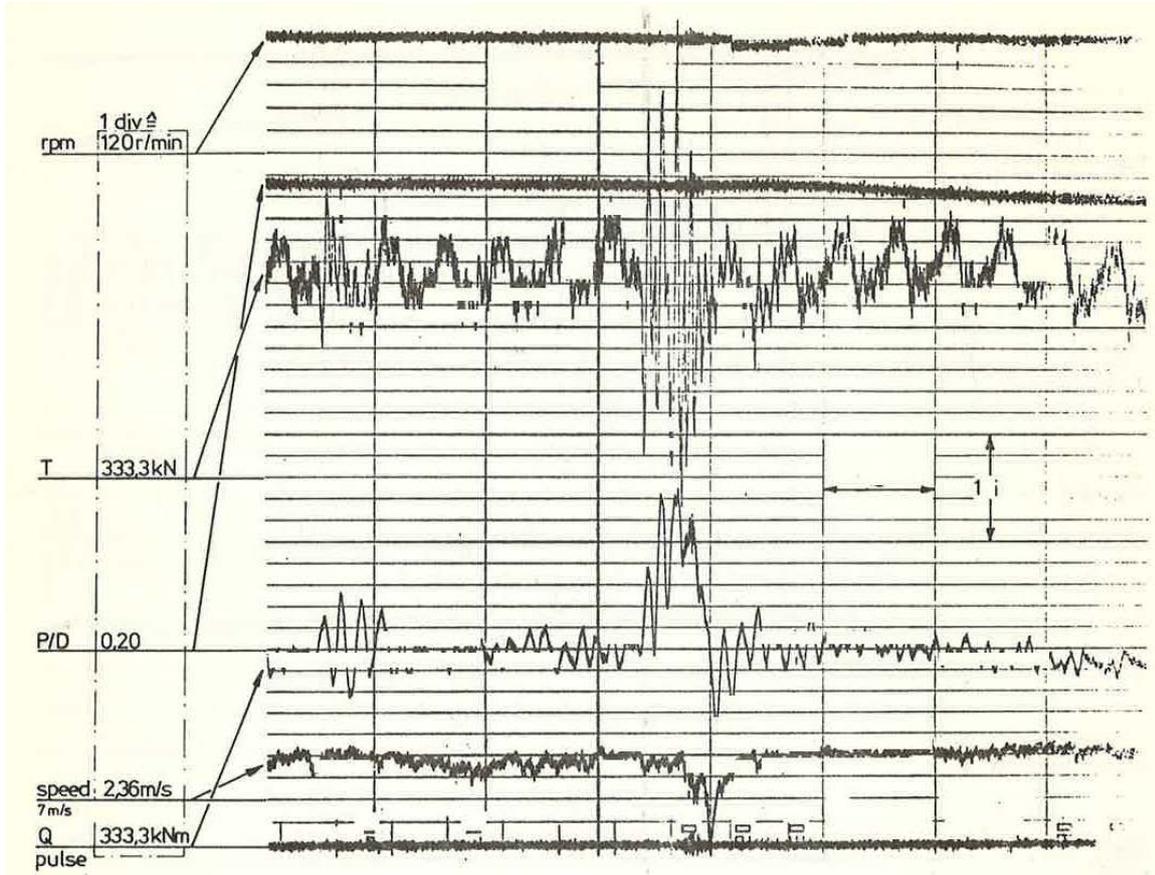


Figure 15. Measured time histories when going ahead in ice clogged channel with two engines, M/T Sotka. Speed drop is very small.

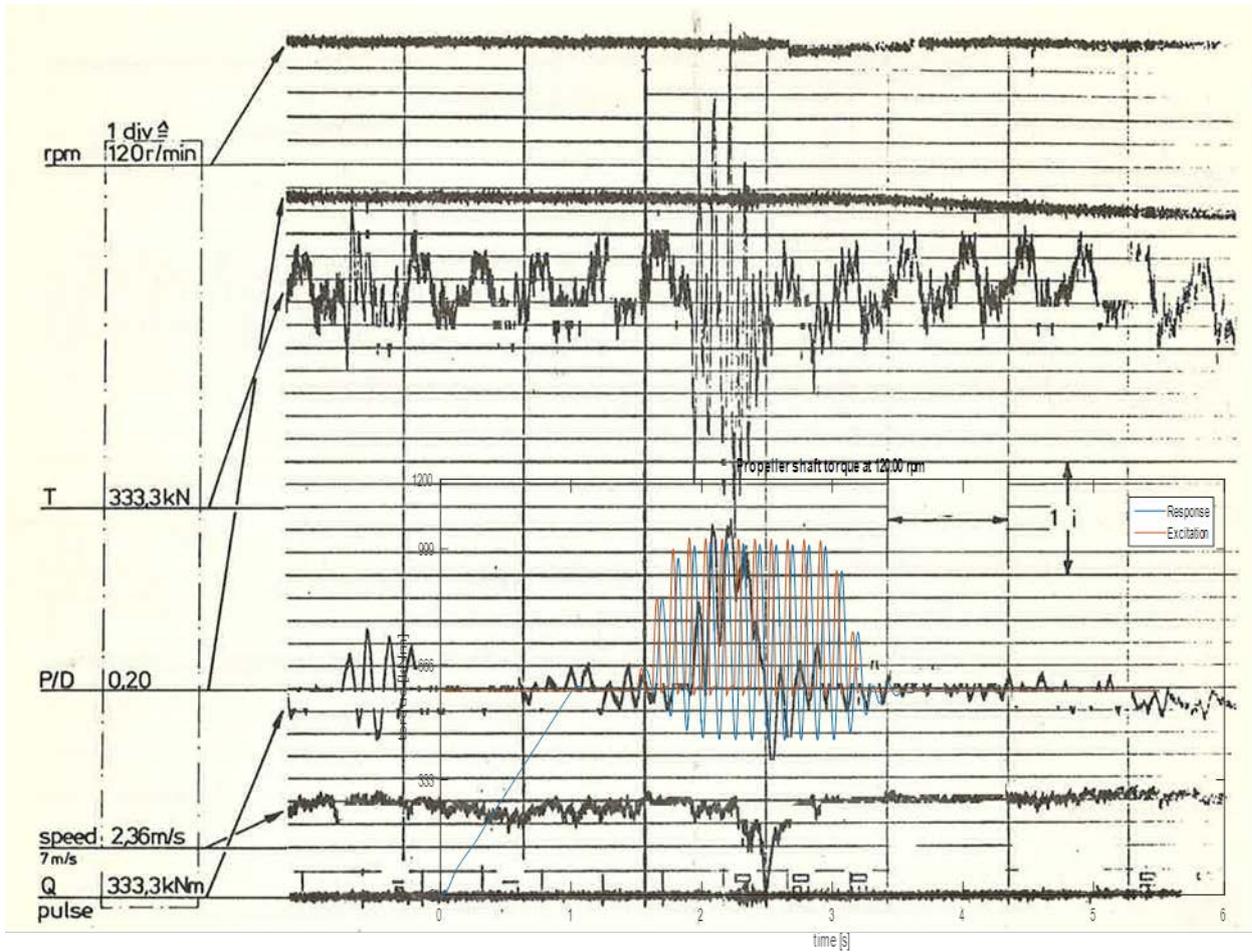


Figure 16. Comparison of measured and simulated torque on M/T Sotka.

6.3 M/V Akademik Fedorov

6.3.1 Comparison case definition

The comparison case for simulation is

- Power 14000 kW
- Speed 139 RPM
- Max torque measured 2189 kNm

Alternate cases

- Power 12000 kW, RPM 140, speed drop 18%
- Power 10000 kW, RPM 132, speed drop 25%

6.3.2 Fedorov Simulation and measurement results

The simulation results for the case with 140 RPM and 14000 kW machine power are presented as torque response from propeller shaft and the propeller speed during ice interaction. The finnish-swedish ice class rule excitation cases 1 and 2 torque patterns were used.

For excitation case 1, the ice torque simulation result is shown in Figure 17 and the corresponding propeller speed in Figure 18.

For excitation case 2, the ice torque simulation result is shown Figure 19 and the corresponding propeller speed in Figure 20

The measured case is shown in Figure 21. It is evident that the torque simulation results for excitation case 1 are qualitatively closer to measured. Simulation results for excitation case 2 are qualitatively different than observed in measurement. Therefore, it is more reasonable to compare excitation case 1 and measurement.

The comparison of simulation and measurement are in Figure 22. Measured and simulated torque values match well.

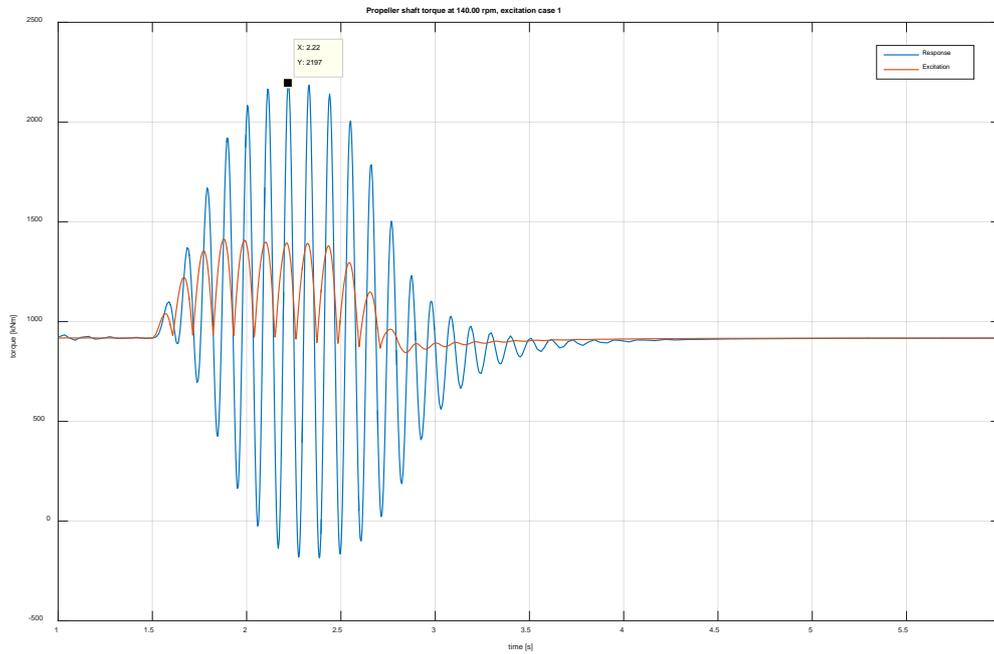


Figure 17. Ice torque on propeller (red) and propeller shaft dynamic response (blue) in ice interaction event, excitation case 1, M/V Akademik Fedorov

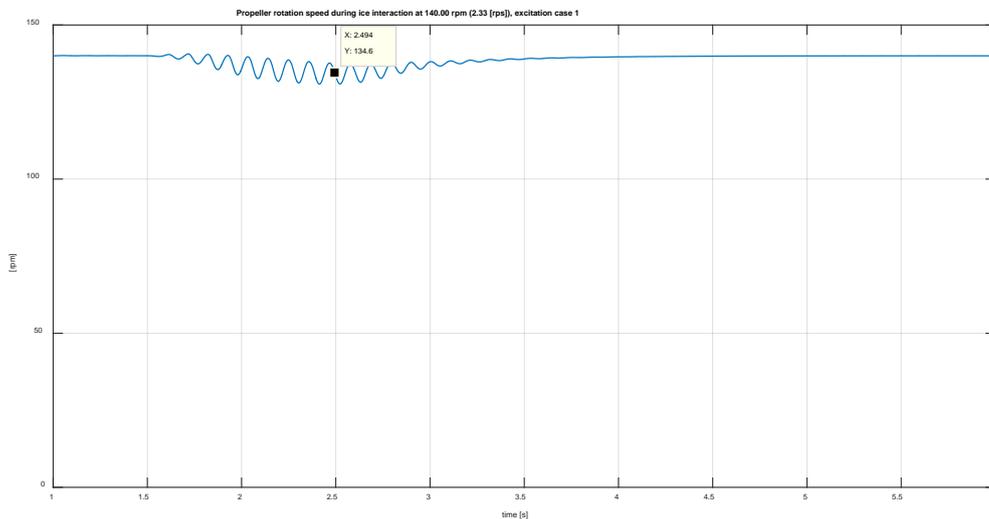


Figure 18. M/V Akademik Fedorov propeller rotation speed in ice interaction event, excitation case 1. RPM drop is small, from 140 to 134 RPM mean value during the event.

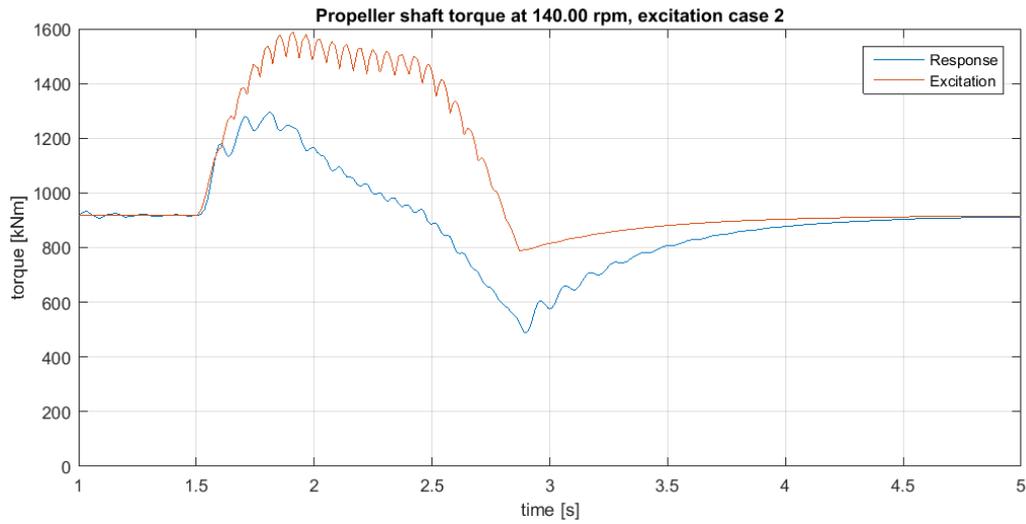


Figure 19. Ice torque on propeller (red) and propeller shaft dynamic response (blue) in ice interaction event, excitation case 2, M/V Akademik Fedorov

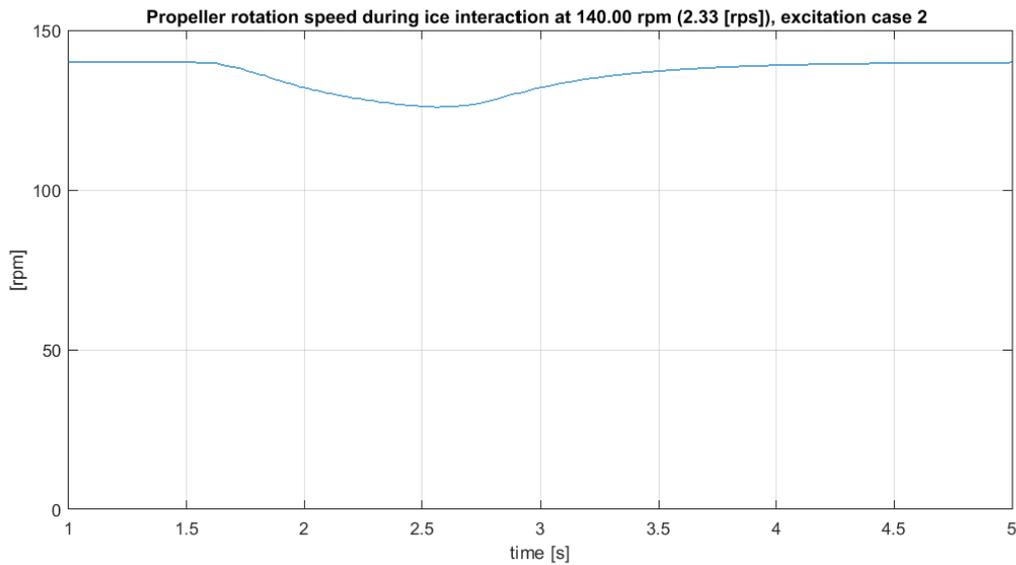


Figure 20. M/V Akademik Fedorov propeller rotation speed in ice interaction event, excitation case 2. RPM drop from 140 to 126 RPM mean value during the event.

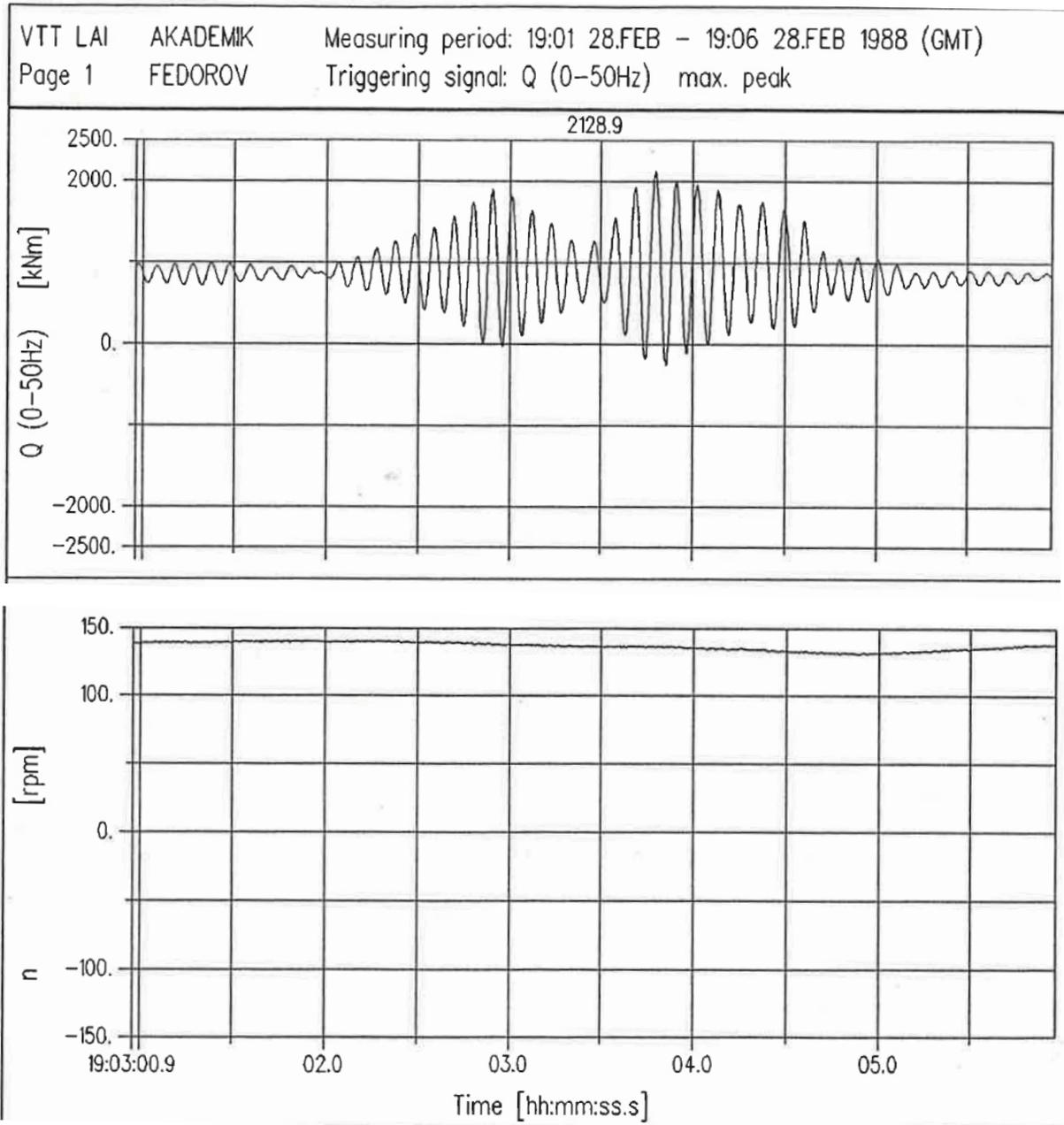


Figure 21. Measured torque on propeller shaft (top) and propeller RPM (bottom).

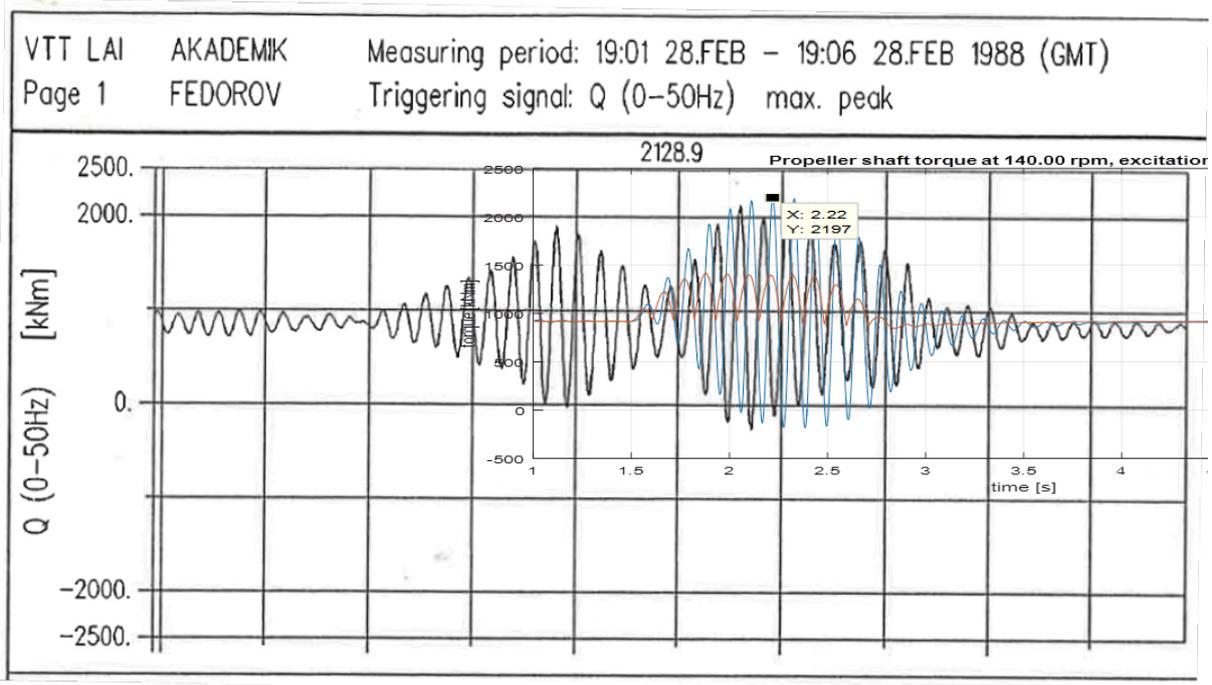


Figure 22. Comparison on Fedorov measured and simulated torque in time domain.

It is a good fit between measurement and simulation with excitation case 1. Speed drop in simulation corresponds well to speed drop in measurement.

7. Conclusions

In general, of the two analysed excitation cases, the ice torque excitation case 1 appeared to give qualitatively closer match to measurements. The shaft response was more like measured torque for this excitation type.

The simulated torque response for M/S Gudingen propeller shaft was approx. 80% of measured torque. The propeller speed drop in measurement is from 360 to 260 RPM, and the simulation indicates similar figures. This corresponds to 28% speed drop.

For M/T Sotka and M/V Akademik Fedorov the torque reserve in the engine / electric drive is significant and speed drop is small. In measurements M/T Sotka indicates 5% RPM drop and in simulation 3%. In measurements M/V Akademik Fedorov indicates about 6% RPM drop and in simulation 4%. Torque response in simulations in both cases matches the measured torque within 5%.

The simulated torque and propeller speed responses are well in accordance with the measured numbers.

The simulated propulsion lines include open propellers. Unfortunately no nozzle propeller were available for simulations.

The most uncertain parts in the simulation models are the motor control model and damping values. These effect to the forced vibration responses as expected.

8. Discussion

The analyses indicated for open propellers, that the simulated speed drop is at reasonable level, but simulated torque response was found to be lower than measured in one case by 20%. This can indicate need to increase the excitation level.

There was no available comparison case for ducted propeller, where both simulation and measurement was possible to achieve. DNV-GL has a case of big ducted propeller (Umiak) that could be simulated with VTT method, in order to understand if the simulation implementation has effect to end result. There is need to further validate the current simulation methodology with ducted propellers.

With the Gudingen case, the excitation case 1 shows agreement in RPM drop, excitation case 2 simulation indicates bigger RPM drop than measured. This apparently is just slightly on the safe side.

For open propeller there are no proposed changes to rules.

For further studies, the torque simulation for ducted propellers is a validation case and for open propellers, the indication that higher excitation level in simulation may be needed to match measured torque.

9. Summary

Three vessels' propulsion shaft lines were modelled with lumped mass- spring – damper dashpot method. The method is used commonly in propulsion torsional vibration analysis.

The models represent the propulsion shaft system dynamics in the sense that their natural frequencies match with the constructions. This is an absolute prerequisite for using the system models for response calculation and can be considered as a necessary quality check.

The ice torque excitation for propeller is taken from Finnish-Swedish ice class rules, where the torque in ice contact is determined in schematical way. The excitation is scaled per ship propulsion based on the propeller diameter and ice block size. In this study, the excitation cases 1 and 2 from the ice class rules was used for response calculation.

The response calculation was performed with MATLAB® in time domain. The models consisted of common mass, damping and stiffness matrices that were used with excitation parameters for propeller and motor(s).

It became evident that the excitation case 1 type torque load was giving closer match to the measured torque in qualitative way than excitation case 2 load.

The results are, for excitation case 1 torque load:

M/S Gudingen : torque response in simulation 80% of measured, propeller speed match

M/ T Sotka : torque response in simulation match measured, propeller speed match measured

M/V Akademik Fedorov : torque response in simulation match measured, propeller speed drom match measured.

However, the models are sensitive to damping characteristics, motor models and excitation estimates. For example, in cases of Gudingen and Fedorov, the observed response differs from the simulated in quantitative way – indicating that there is likely more complex excitation mechanism or ice load pattern than is estimated in the ice class rule.

The simulated propulsion lines include open propellers. Unfortunately no nozzle propeller were available for simulations. It would be good to find a ducted propeller case where measurement data is available, for simulation method validation.

References

1. Kinnunen, A., Computation of response for ice loads in marine propulsion systems. VTT Research Report VTT-R-000682-07, 2007, VTT, Espoo Finland.