Propulsion Shaft Line Ice-Induced Dynamic Torque Response Calculation and Comparison to Full Scale

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ABSTRACT

Winter and arctic conditions set specific requirements for ship design in the form of ice-covered water. One major aspect is propeller and propulsion design for ice conditions. The propeller-ice interaction has been widely studied over the years and there are current regulations among classification societies to ensure safety of ice-going vessel propulsion design. The design process involves propeller dimensioning for ice loads as well as rest of the propulsion line. The propeller-ice interaction causes torque loading to the propulsion system. This is dynamic in nature and is somehow to be dealt with in design phase. In this paper, the principle of dynamic propulsion shaft line model is presented, the model is validated with ship design torsional vibration analysis calculations and the time domain response calculation is performed with ice class requirements, and these results are compared with full scale measurements.

In full scale tests, the propulsion shaft line input torque from propulsion motor was measured simultaneously with rotating speed. By comparing the measured and simulated dynamic response, it is possible to backward determine the magnitude of ice torque excitation.
In conclusion, the propulsion shaft line dynamic ice-induced torque response in the measurements was significant, even so that the ice class required excitation level for simulation was underestimating the torque response level encountered in measurements.

KEY WORDS: Propeller ice torque; response simulation; full-scale measurements

DYNAMIC TORQUE MODEL FOR PROPULSION SHAFT LINE

Model Principle

The model is built on simplification of the ship propulsion shaft system. The shafting is simplified to lumped masses, stiffnesses and dampings. The approach is well used in the shipbuilding industry for the torsional vibration analysis of the propulsion systems. In general it is used for estimating the torsional natural frequencies and also for placing a correct flexible coupling in the system.
The simplification is presented in schematic way in Figure 1, where the \( J \) denotes rotational inertia, \( k \) refers to torsional stiffness, \( c \) means torsional damping and \( T \) is referring to external torque to the system, like motor torque or propeller resistance.
The equation of motion for this type of system is simply written in matrix form

\[
[J]\{\dot{\phi}\} + [C]\{\dot{\phi}\} + [K]\{\phi\} = \{T_{\text{ext}}\}
\]  (1)

The angular displacement is described with the variable \(\phi\). When this type of system includes gears, they must be taken into account for deriving the system matrixes.

The propeller hydrodynamic model is well-known torque-rotation speed dependency from propeller theory (Carlton, 2012):

\[
Q = KQ\rho n^2 D^5
\]  (2)

The propeller torque \(Q\) is described with torque coefficient \(KQ\), water density \(\rho\), propeller rotation speed \(n\) and propeller diameter \(D\). The torque coefficient is generally function of the propeller advance coefficient \(J\), but in this simulation case the \(KQ\) is assumed constant, because ship speed is assumed to remain constant throughout the short-duration propeller-ice contact event.

Engines or electric drives used in ship propulsion systems are modelled as torque sources, with PID controller or similar means to provide functionality corresponding to the actual motor response.

The practical implementation was done with MATLAB® Simscape, and the appearance of model can be observed in Figure 2.
Figure 2. The modelling view: Electric motor (on top left) connected to Z drive propulsion unit model. Shafts are represented with stiffness parameters. Couplings, gears and propellers include inertias as well.

**Dynamic Shaftline Model Validation**

The model dynamic properties are usually checked to be the same as are used in the ship design torsional vibrational analysis (TVA). The model set-up for TVA is used to calculate the first few natural frequencies and the MATLAB model for response calculation is checked to reproduce the same first natural frequency. This is sufficient because the propulsion shaft line dynamics related to propeller blade frequency excitation is usually dominated by the first torsional mode.

For the modelling method validation as such, a comparison of model results with three full scale cases was made and good agreement was found. (Kinnunen, 2017)

**Modelling Ice Excitation: Ice Class Rule Requirements**

The propeller-ice interaction resulting into propeller torque is addressed in IACS and Finnish-Swedish ice class rules in the form of additional torque on top of the hydrodynamic torque. The representation of the torque is based on full scale experience and propeller-ice interaction simulation. The propeller-ice interaction simulation (e.g. Veitch 1995, Veitch 1997, Soininen 1998, Kinnunen, 2015) is laborious task and requires rather extensive set of input data. The ice torque calculation, as presented in the ice class rules, relies on determining the maximum ice torque for the propeller in question and using that together with a predetermined torque load pattern to the propeller. The load patterns used in this study are from Finnish-Swedish ice class rules 2010 version.

The definition of ice torque is expressed as a function of propeller shaft rotational degree of freedom in following way:
\[ Q(\varphi) = C_q Q_{\text{max}} \sin \left( \frac{\varphi 180}{\alpha_i} \right), \varphi \in [0..\alpha_i] \]  
(3)

\[ Q(\varphi) = 0, \varphi \in (\alpha_i ... 360] \]  
(4)

Here the parameter \( Q_{\text{max}} \) is the maximum ice torque in ice contact, \( C_q \) is amplitude scaling factor relating to ice torque case, \( \alpha_i \) is the ice torque impulse length in propeller shaft rotation angle. Angular variables in these formulas are in degrees. The torque load cases in the rules are schematically presented in Figure 3.

Figure 3. Ice torque load sequences according to Finish-Swedish ice class rules. On the left; excitation case 1, in middle excitation case 2, on the right excitation case 3.

Simulation Result Example

The simulation results provide the time-domain estimates for the propulsion system response to ice excitation. The propeller shaft response to Finnish-Swedish ice class rule ice torque load excitation case 1, together with the ice excitation is presented in Figure 5.

Figure 4. Propeller shaft response to ice torque excitation.

THE FULL SCALE MEASUREMENTS

The full scale measurements were done during winter 2016, in Bothnian Bay, the northernmost region of Baltic Sea. The main purpose of the ice trials was to verify the performance of the propeller in ice conditions. The ship was equipped with two Z-drive type
azimuthing propulsion units, that is, the propeller is driven with motor inboard the vessel via two bewel gears. The machinery arrangement was diesel-electric, i.e. main engines drive generators, and propulsion units are driven by electric motors. Propellers are fixed pitch propeller. The measurement setup consisted of measuring input shaft torque and RPM with the steering angle of both propulsion units simultaneously. Ship speed was recorded with GPS. In Figure 5 is the propulsion system principle and measurement location.

Figure 5. Z-drive type azimuthing propulsion unit principle. A: propeller, B: lower gearbox, C: upper gearbox, D: electric drive. Measurement of torque and RPM on the input shaft of propulsion unit.

The ice conditions were good for ice trials, at least 0.8 m solid ice with lots of ice ridges. The conditions are at least comparable to the IA Super ice class in Finnish-Swedish context. The ice channels on the area were in normal condition. The ice properties were studied with compression tests in-situ and the ridges were observed by drilling. The compressive strength samples were taken from solid ice, values are presented in Table 1. The two checked ridges were 4.25m and 2.55m total height. Temperature on the area was between \(-2 \text{ to } 0\)°C.

Table 1. Compressive strength of ice observed on site.

<table>
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<tr>
<th>Sample id</th>
<th>Uniaxial compression strength [MPa]</th>
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<tr>
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<td><strong>St dev</strong></td>
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**COMPARING MEASUREMENT AND SIMULATION**

The comparison of measurement and simulation is done for torque and RPM on the input shaft of the propulsion unit. In Figure 6 is compared the maximum measurement result and the simulation result for Finnish-Swedish ice class IA Super excitation case 1.

Figure 6. Comparing measured and calculated response from input shaft. Overview on left and detail on the right. Calculated torque clearly lower and longer ice-contact than measured.

Figure 7. Input shaft speed comparison. Simulation with FSCIR ice class IA Super excitation.

The measured response is clearly higher in amplitude and shorter in duration than what the IA Super ice class excitation causes in simulation. This leads to question: how much ice torque excitation the simulation needs to match simulated response to the measurement? The
simulation ice load sequence duration is scaled to 50% of the original and amplitude increased by 75%, then the simulation result is closer to the measured, see Figure 8.

Figure 8. Comparing measured and calculated response (overview on the left, detail on the right) from input shaft. Excitation duration shortened by 50% and amplitude increased by 75% compared to the Finnish-Swedish ice class rule IA Super requirement.

CONCLUSIONS

The dynamic torsional model of the propulsion shaft line was constructed with a lumped mass method. The electric drive in the model was a controlled torque source and the ice torque excitation was taken from ice class rules (FSICR IA Super). The dynamic model properties were checked to match the ship design time torsional vibration analysis results. The time domain response calculation was done with MATLAB® Simscape environment. The full scale measurements provided data for propulsion shaft line input speed and torque. The measured torque is considered as a system response to the ice torque load at the propeller. The measurements were compared to the ice class required simulations and it was noted that the measurement gave higher response than the simulation suggested. The simulation
response was scaled by scaling the ice torque load at the propeller, and good match of simulated response was found to the measured response by this method.

In conclusion, it is reasonable to say that the dynamics in the shaft line system is in significant role in determining the actual torque level in operation, and that the ice class-required dynamic ice torque load for the propeller is not conservative in this case.

It is also worth to remember that the full scale test was short, two ice days, and such a good ice load was encountered during that time. The simulation based on the ice class excitation is trying to represent the maximum loading over service life of the vessel was indicating lower values.

ACKNOWLEDGEMENTS

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