OPERATION OF THRUSTERS IN ARCTIC WATERS ARCTIC THRUSTER ECOSYSTEM

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Abstract. Due to collisions between ice and propeller the drive train of ice breakers in artic conditions is a highly stressed system. Aim of the ArTEco 'Arctic Thruster Ecosystem' project is to increase the reliability of vessels when overloads and torsional vibrations occurs.

To achieve this aim different load scenarios will be analysed on a test rig located in Tuusula (Finland). Here the WST14 azimuth thruster, which is equipped with measuring instruments, is operated by the VTT and Wärtsilä. To investigate the behaviour of the test rig and the thruster different simulation models are created. These multibody system simulation (MBS) and finite element models (FE) are required to understand the behaviour of the thruster and investigate improvement strategies. Targets of these investigations are the dynamic behaviour during ice contact and the optimization of bevel gears in prospect of safety and efficiency. Therefor estimated propeller loads that occur during ice contact of the gear box housing or loads occur by hitting the propeller blades are used.

The simulation models of the thruster regards the flexible structure of the housing and shafts. Using this information the comparison considers natural eigenfrequency correlates to the test rig in Tuusula and the misalignment of the bevel gear can be investigated, validated and an optimisation achieved. For further analysis a simulation model is assembled by TU Dresden and verified by several time based data sets and modal analysis of the test rig. That way overloads and high dynamic loads which can't be applied on the test rig are evaluable. Besides the dynamic analysis a progress in design phase for bevel gear stages is done. This is achieved by using complex FE models including the elastic bevel gear contact, bearing stiffness, clearances and the support of the flexible housing. The complex load and temperature condition lead to different displacements of the gears. Using simulation based displacement data and the software BECAL [1] a precise contact pattern can be investigated to determine safety factors, damage sum and efficiency.

To investigate the possible efficiency improvements of a bevel gear a design process is described. Therefor a variation of macro- and micro geometry were made. Point of interest is to shift the theoretical pitch cone relative to the contact pattern, to reduce the local sliding speed. The combination of profile shifting x_{hm1}, pressure angle α_{dD} and profile crowning c_{Pz} modification leads to a significant efficiency improvement.

1 INTRODUCTION

The main objective of the ArTEco project is an improvement of ship drive trains in arctic conditions, with the target to identify critical areas in ship propulsion design and improve products for this industry. The thruster test facility established in Finland at the end of 2013 achieved a significant progress in conceptual development. Test facility allows measurements in a way that is not possible when a unit is in operation. These facts led Wärtsilä to establish the propulsion test facility, the Wärtsilä Propulsion Test Centre (WPTC) in the Helsinki area together with the VTT. A 2 MW thruster can be run with full power at the test rig in Tuusula and the operational loads can be applied to the thruster by 11 hydraulic cylinders.

The facility offers a so far unique possibility to make technology progress suitable for future marine thrusters. The test rig allows the measurement of bearing loads, gear displacements and shaft torque. Furthermore, oil temperatures, shaft displacements and vibrations can be monitored. As shown in Figure 1, the thruster housing is mounted on the structure of the test rig and the drivetrain is connected to an electrical motor and generator to apply torque and speed to the drivetrain. Six hydraulic cylinders can be applied on loading unit at the end of the propeller shaft, to apply thrust and side forces and five on the thruster housing. The cardan shaft, which connects the propeller shaft with the gearbox input shaft. With an electric connection between generator and motor, it is possible to feed only the power losses to the system and use the generator's energy to run the motor. In Figure 1, the load introduction points are marked by red arrows.

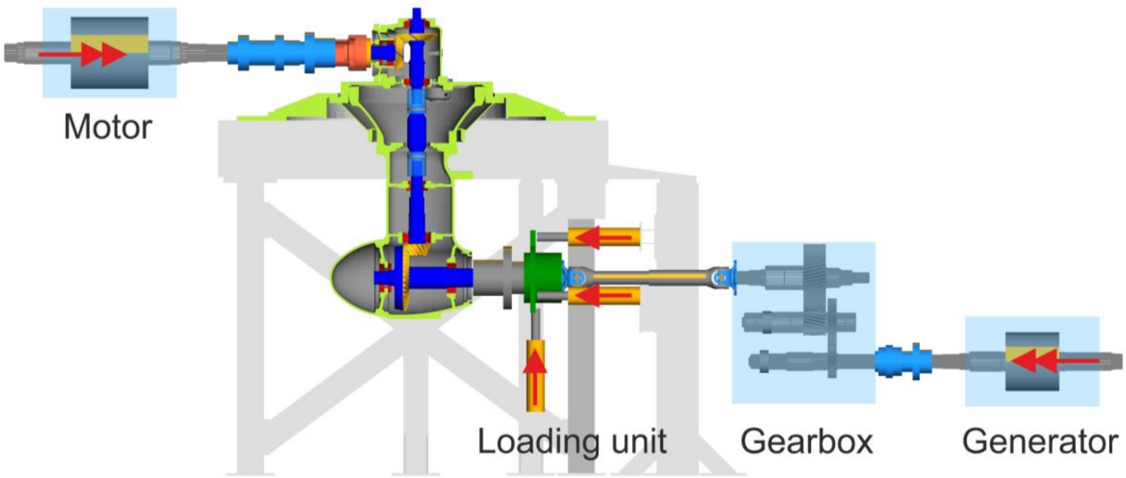

Figure 1: Simulation model, the red arrows indicate the load introduction points

The institute of machine elements at TU Dresden develops the software BECAL (BEvel gear CALculation) which is an analysis tool for bevel gear design and safety evaluation. It was developed by the Institute of Machine Elements and Machine Design in corporation with the Institute of Geometry of the TU Dresden on behalf of the Drive Technology Research Association (FVA) [9]. The dynamic drive train behavior gets investigated using MBS methods since 2001. With these expertise the investigation of large drive trains, typical for ships, roller mills, compressors, fans, shearers, cranes and wind turbines represent one of the main focuses of research in recent years [3], [4], [5].

2 TEST RIG AND SIMULATION MODELS

The motor and generator are the system boundaries of the drive train, with the thruster and the deceleration gearbox placed in between. The flexible structure of the thruster housing including the plate structure of the test rig is part of the simulation model as well. The connection to the floor is not considered, due to its high stiffness compared to the other components. The displacement behavior of the Thruster in the MBS Model is validated with an FE model including elastic housing, shafts, bearings, and gear contact (Figure 2).

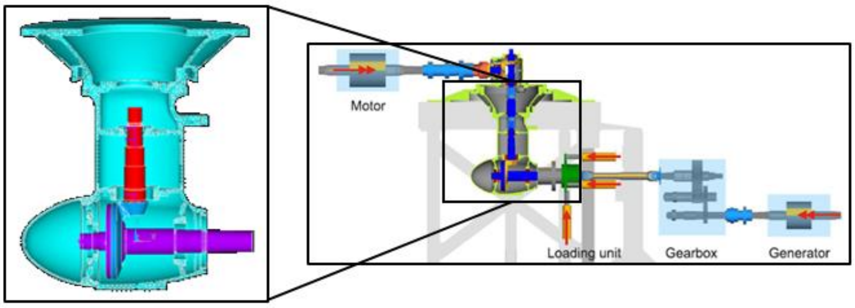

Figure 2: FE model (left) and MBS model (right)

Before using the possibilities of the different simulation models the test rig gives the opportunity for validation. The validation is done by using the measurement results from modal analysis and time domain torque and displacement signals. The dynamic behavior of the test rig is determined by acceleration sensors during a modal analysis. The MBS model is using information about inertia and stiffness of the drivetrain components to calculate the natural frequencies of the test rig. The natural frequencies of the torsional system, the 6-DOF-MBS model and measurement results are compared in Figure 3. The comparison of simulated and measured natural frequencies of the thruster mode shapes in longitudinal, transversal and vertical direction shows a good agreement.

With the validated model, the system behavior can be predicted and tests can be rerun to analyze bearing loads and bevel gear stress with BECAL [1]. The FE model is already in use to calculate the bevel gear misalignment for the ongoing design procedure. In the current design process overload scenarios that represent the arctic loading spectrum are calculated and safety parameters are analyzed before they are applied to the test rig.

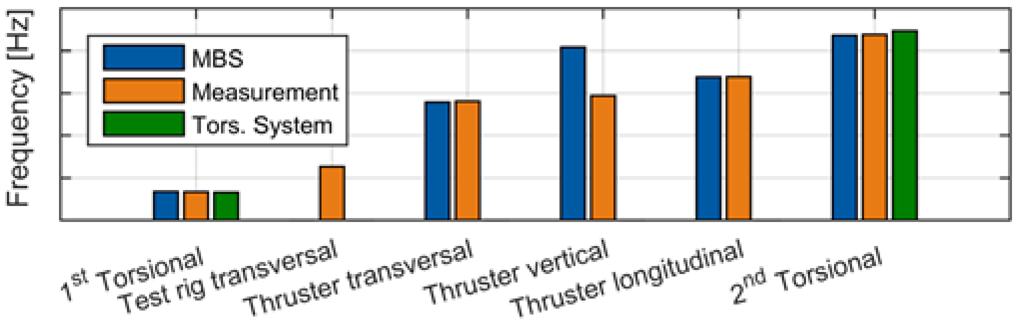

Figure 3: Comparison of natural frequencies of simulation model and measurement

3 BEVEL GEAR DEVELOPMENT

The developed FE and MBS models are used to design a new stage of bevel gears for the considered thruster. Figure 4 illustrates the workflow for the design process using the FE model and the software BECAL.

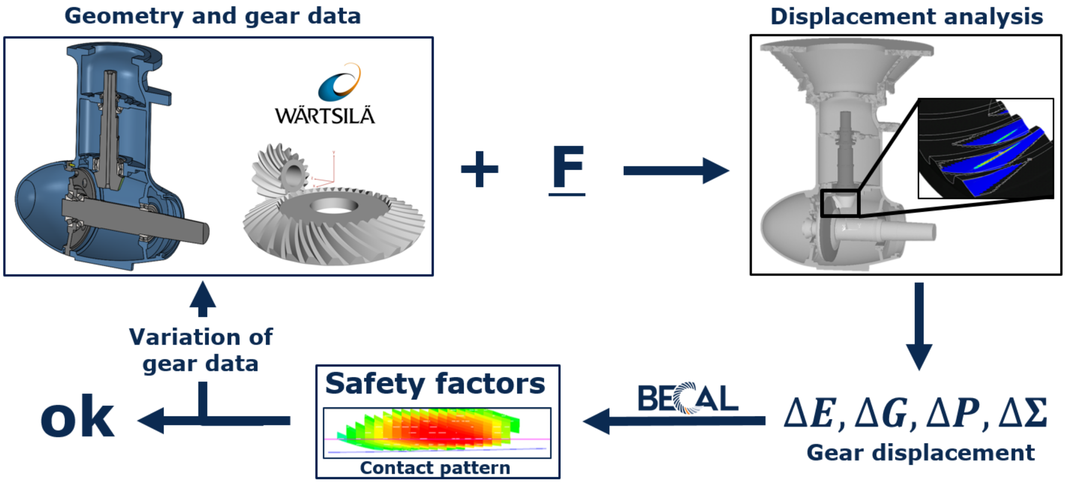

Figure 4: Design studies for bevel gear geometry

The occurring load vector $\underline{F}$ is a crucial input parameter which correspond to the propeller loads during vessel lifetime. Investigation of arctic conditions leads to determine the load spectrum of the drive train. Resulting from the flexibility of the thruster housing, shafts and bearings, the reaction of the gear is a misalignment. This leads the contact pattern to shift from an ideal position to heel or toe and root or tip. Adjustment of the micro geometry of the tooth flank has to be done. Especially lead crowning, profile crowning and angular modifications are used to ensure a centered contact pattern. With the results of the displacement analysis, BECAL allows conclusions regarding the safety factors of the gears [1]. Optimization target in this workflow is mainly to lower the Hertzian contact and root stress. For the nominal load the second developmental stage of the Tuusula bevel gear results in 11 % reduction of the Hertzian stress (Figure 5).

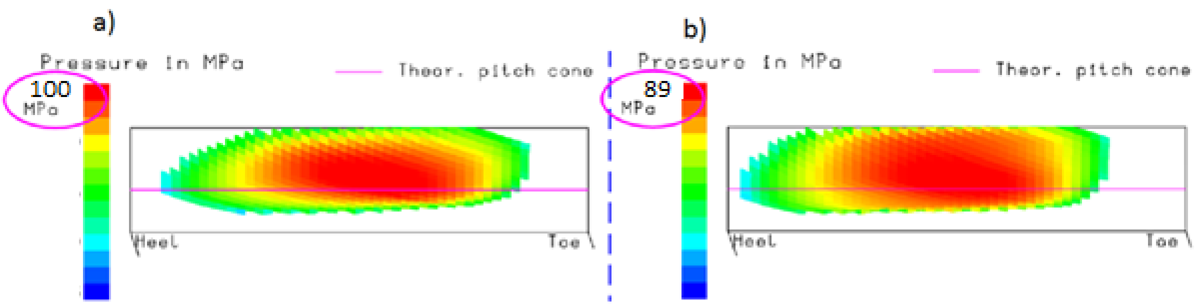

Figure 5: Reducing the Hertzian contact stress of the thruster bevel gear for nominal load
a) developmental stage one, b) developmental stage two

4 ARCTIC CONDITIONS - ICE LOADS

One target of the ongoing investigation is to determine the load spectrum of arctic conditions. In cooperation with the VTT, a MATLAB tool for ice load simulation is created. These impact tool can be connected to the MBS model to investigate the load spectrum of arctic conditions. Ice peak loads corresponds to ventilation, radial ice contact and ice crushing, which determines the propeller forces and probability according to [2], [6], [7]. These load spectrum can be applied to the Tuusula test rig via several hydraulic cylinders or ice blocks that mechanically hit the thruster housing. The IAS ice class represents the heaviest ice loads in the Finnish-Swedish ice class rules [6]. Figure 5 presents the ice load probability and amplitude for an open propeller (IAS) with the dimension of the investigated thruster in Tuusula. To describe the ice load probability a Weibull distribution is used [7]. The 100 % load amplitude in figure 6 represents the nominal load of the thruster.

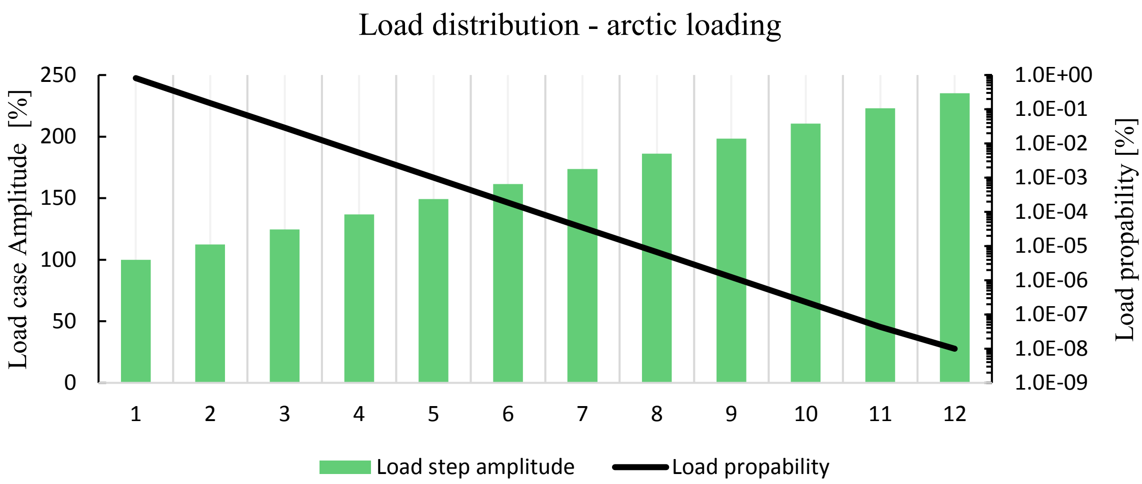

Figure 6: the ice load probability and amplitude

BECAL gives the opportunity to calculate a damage accumulation for every local point on the flank [8]. The ice load distribution is used to calculate a Miner elemental accumulation for the bevel gear design stages. To validate the new stage of development the load distribution is calculated for a thruster operating in the IAS ice class for a lifetime of 5 years with nominal load. With the new variant the damage accumulation of the pinion flank can be reduced by 55% (Figure 7).

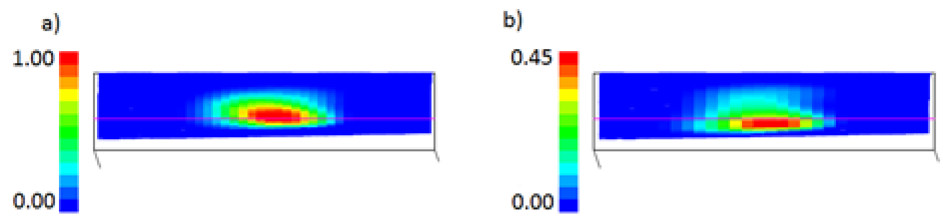

Figure 7: Normalized damage accumulation for the pinion flank a) stage one b) stage two

5 EFFICIENCY INVESTIGATION

After enhancing the load capacity another point of interest is to improve the efficiency. With BECAL a local gear loss can be calculated. For each point on the flank (Y) the local gear loss P_{VZP} is calculated by the formula (1). It is related to the local normal load $F_n(Y)$, the local sliding speed $v_g(Y)$ and the local friction coefficient $\mu(Y)$. The sum gear loss $\overline{P_{VZP}}$ is calculated for the overall mesh with formula (2).

$$P_{VZP} = \mu(Y) \cdot F_n(Y) \cdot v_g(Y) \quad (1)$$

$$\overline{P_{VZP}} = \frac{\sum\sum \mu(Y) \cdot F_n(Y) \cdot v_g(Y)}{m} \quad (2)$$

To investigate the possible efficiency improvements a test program will be done at the local bevel gear test bench located in Dresden. Therefor a variation of macro- and micro geometry of the test bench design where made. Point of interest is to shift the theoretical pitch cone relative to contact pattern, to reduce the local sliding speed. The aim is a pitch cone near to the middle of the contact pattern. Variation parameters are profile shifting x_{hm1}, profile crowning c_{Pz} and a profile angle modification $H_{\alpha z}$ (Figure 8).

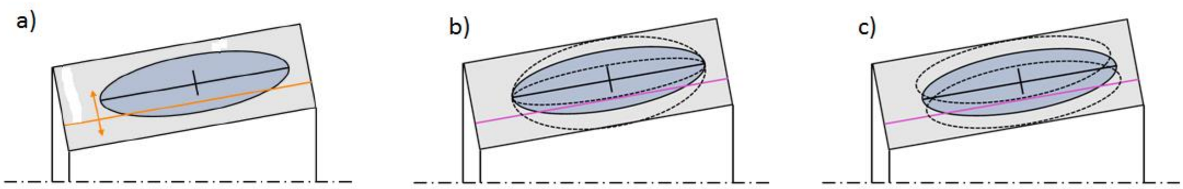

Figure 8: Variation of a) profile shifting x_{hm1} b) profile crowning c_{Pz} c) profile angle modification $H_{\alpha z}$

To investigate these effect four different bevel gear designs are made. The contact pattern of these efficiency variants are presented in Figure 9. In the first step the profile shifting x_{hm1} is reduced from 0.5 (Variant A) to 0.3 (Variant B). Furthermore the profile crowning is increased from 50 to 150 µm (Variant C) and in the last step the pressure angle α_{dD} is modified from 20° to 22° (Variant D). The combination of profile shifting x_{hm1} , pressure angle α_{dD} and profile crowning c_{Pz} modification leads to a significant efficiency improvement. The bevel gear losses are reduced by 34 %. These results will be validated at the local test bench located in Dresden.

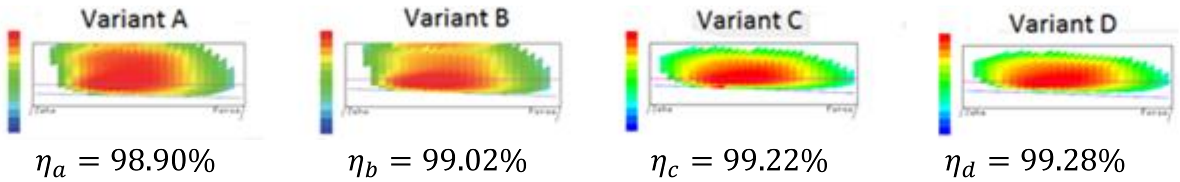

Figure 9: Hertzian stress for the macro - and micro - geometry variants

6 CONCLUSION

The test rig established by the VTT and Wärtsilä gives all partners a better understanding of the complex behavior of azimuth thrusters. It provides the opportunity to analyze the systems behavior, which cannot be done during operation of a vessel. Several overload tests are executed to describe the drive train behavior under the load spectrum of arctic conditions. Further tests to detect the effect of biodegradable oils on gear fatigue and efficiency are planned. The interaction of test rigs and simulation models deliver a huge benefit for the participants of the Arctic Thruster Ecosystem project. Due to the time- and cost-efficient design studies a big step in improving the bevel gear design for thruster applications is already made and currently tested in Tuusula.

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