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BEVEL GEAR CALCULATION OF A VESSEL DRIVE TRAIN WITH AZIMUTHING THRUSTERS

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Abstract. Increasing requirements to modern vessels concerning performance and manoeuvrability led to very complex drive train designs. Therefore azimuthing thrusters became very common in the area of offshore supply vessels, tug boats and specialized research vessels. In order to extend the already huge field of operation and to better understand dynamic effects in such azimuthing thrusters the research project "EraNet HyDynPro" was started. The project focuses on the design of a robust drive train which contains a bevel gear stage. Therefore loads caused by propeller-water-interactions as well as loads while operating under ice conditions will be analysed. Based on this interdisciplinary project a contemporary way of gear calculation will be shown in this paper. For gear calculation it is necessary to acquire design loads. These can be measured at high costs or be simulated numerically. In the last few years the Multi-Body-System (MBS) Simulation got more and more popular to determine static and dynamic properties of large drive trains. This simulation can contain mathematical models of the propeller behaviour inside the water and under ice conditions as well as models of the electrical motor. Based on this a good prediction of gearing loads is possible. By the knowledge of the gearing load time series a complex tooth contact analysis can be made for every arbitrary point in time using specialized gearing software. Gear tiltings are considered in order to calculate the load distribution on the tooth flanks. By this knowledge a local comparison of the load and load capacity can be carried out. But how to handle the vast variety of load situations during different load cases and long time series? Therefore an appropriate classification of the different occurring states of gear deviations and gear loads will be presented. This way we are able to determine the risk of common gearing failures like pitting and tooth root breakages in detail for individual drive trains under different operating conditions. The paper will present the procedure of this contemporary way of designing gears. By using a simple spur gear set the general idea of simulating the operating conditions of a drive train and the subsequent complex tooth contact analysis

will be explained. On basis of this information a suitable approach to assess the risk of different gearing failures is carried out and the results will be illustrated.

1 INTRODUCTION

Modern ships are more and more subject to higher requirements. This specially applies to specialized ships like offshore supply vessels, tug boats and research vessels (see figure 1). In addition those vessels often operate under ice conditions, whereby specific requirements to the entire drive train arises. In the research project "EraNet HyDynPro" the total set of processes concerning the drive train are investigated more closely. At this the propeller-ice-interactions as well as the loads under ice conditions get analyzed. Influences caused by the driving engine as well as load alternations within the drive train caused by native mass and stiffness distributions are considered by a *multi-body-system simulation* (MBS-simulation). The focus of this paper is the calculation and design of the gearing system. One essential intermediate target of the research project is the generation of chronological load and position series of the gear wheels. These series get classified and every single class is applied to a *complex gearing load analysis*. Subsequently the local amount of damage is calculated and a local total damage sum gets generated using an appropriate damage accumulation approach for every kind of damage (pitting, tooth root breakage, flank breakage...). This damage sum represents the amount of locally utilized capacity of the gearing system with respect to the kind of damage.

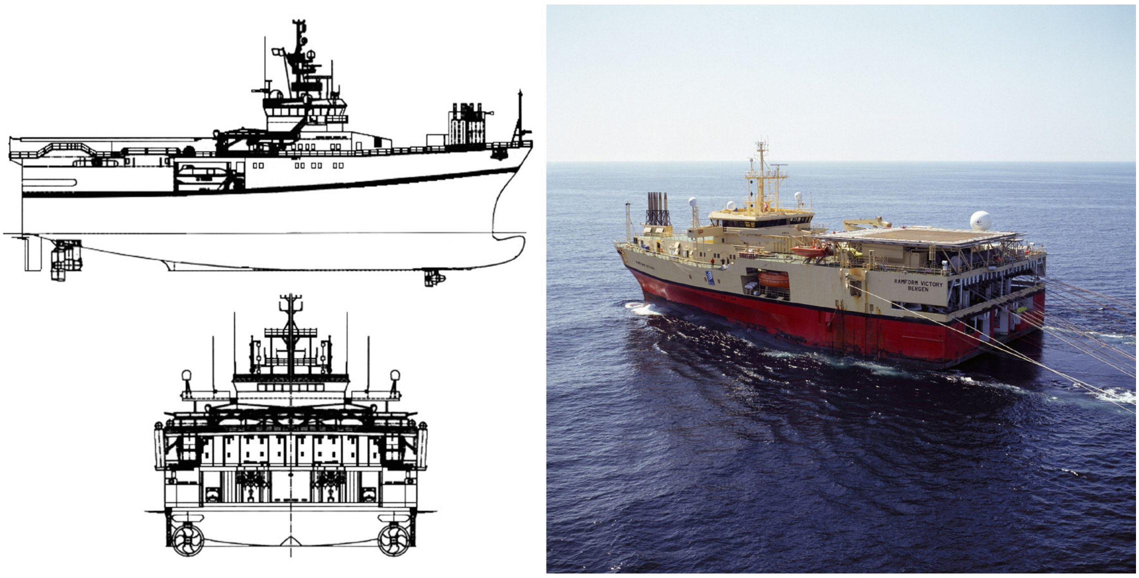

Figure 1: Research vessel with azimuthing thrusters

2 LOAD DETERMINATION

Usually the determination of design loads, or possibly their chronological trends, is the point of origin when calculating machine elements like the gearing system.

2.1 Determination of gearing loads and gearing displacements

In the case of stationarily operating and stiffly mounted drive trains the load alternation is very low. This way the nominal torque, which is necessary for the calculation of the toothing system, can be calculated using the input speed and power together with transmission ratios.

Conventional vessels operate in a quasi-stationary manner. Therefore the load alternations during operation are less important as long as resonance effects are avoided. However the mentioned specialized vessels are operating with severely alternating input power and speed during maneuvering. Beyond that the housing of an azimuthing thruster is a relatively flexible foundation for the drive train. For these circumstances it is necessary to perform detailed investigations of the dynamic behavior of the entire drive train system. Therefore a complex MBS-simulation model is built up (see figure 2). This model is a multi-dimensional oscillation system generated by masses, stiffness and damping. External loads caused by the motor and the propeller are applied to the model by co-simulations or characteristic curves. Based on this some chronological series of tooth forces and gear wheel positions can be calculated and recorded for a variety of operating conditions.

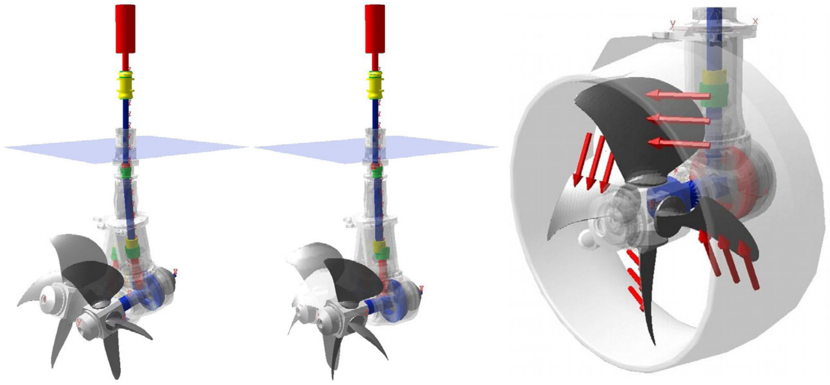

Figure 2: MBS-models of azimuthing thrusters: Two exemplary mode shapes (left, center), force application on the propeller (right)

2.2 Generation of combined load-displacement-spectra

A gearing calculation based on chronological series of the tooth forces and gearwheel displacements is hardly practicable. Hence a multi-dimensional classification of the tooth forces on the one hand and gear wheel displacements on the other hand is appropriate. In this way the tooth calculation for every point in time is not necessary. It is sufficient to do this for every field of classification only, whereby the calculation effort decreases rapidly. [1]

In case of spur and helical gears an acting deviation of the flanks can be calculated using the displacements of the gear wheels. These, the tooth normal force and several geometrical parameters of the gearing are the required input data for the complex gearing load analysis (see figure 3).

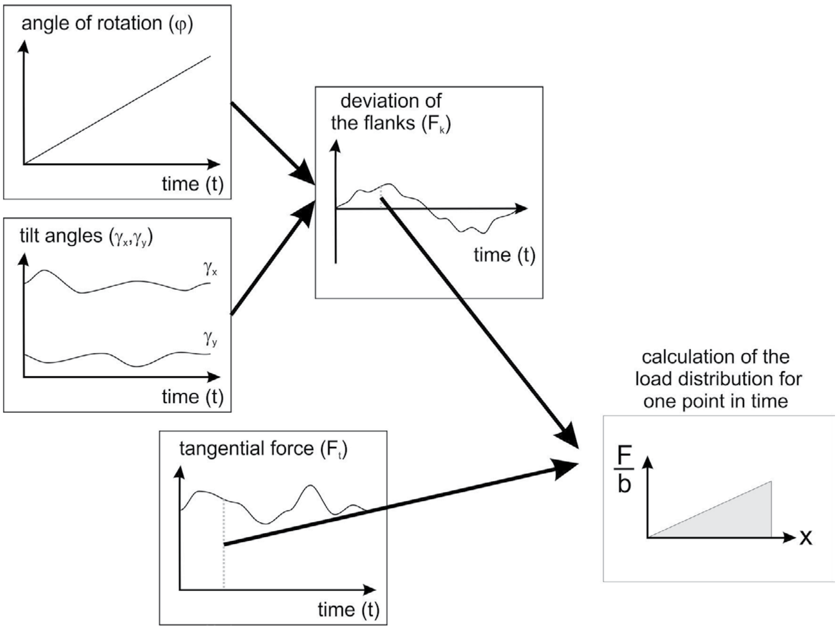

Figure 3: Scheme of data supply for the complex gearing load analysis

3 SPECIALISED GEARING CALCULATION

To avoid the common toothing failures like pitting and tooth root breakages at stationary operating and stiffly constructed drive trains a standardised gearing calculation according to DIN 3990, ISO 6996 or similar is applicable. If shaft, bearing, gearwheel or housing deformations influence the gearing system significantly, a verification by a complex gearing load analysis is advisable. Beyond that gearings of industrial applications more and more fail by a kind of damage called *flank breakage* or *tooth interior fatigue fracture* (TIFF). Up to now there is no standardized calculation available against this kind of failure. [2, 3]

3.1 Calculation of the tooth load distribution using the complex gearing load analysis

To perform a complex gearing load analysis the chair of machine elements of the technical university Dresden developed the computer software *LVR* for spur and helical gears as well as *BECAL* for bevel gears. These programmes enable the determination of the local load distribution on the tooth flanks for all meshing positions at arbitrary torque (see figure 4). Thereby shaft deflections, gearwheel and bearing displacements as well as the tooth deformations are considered.

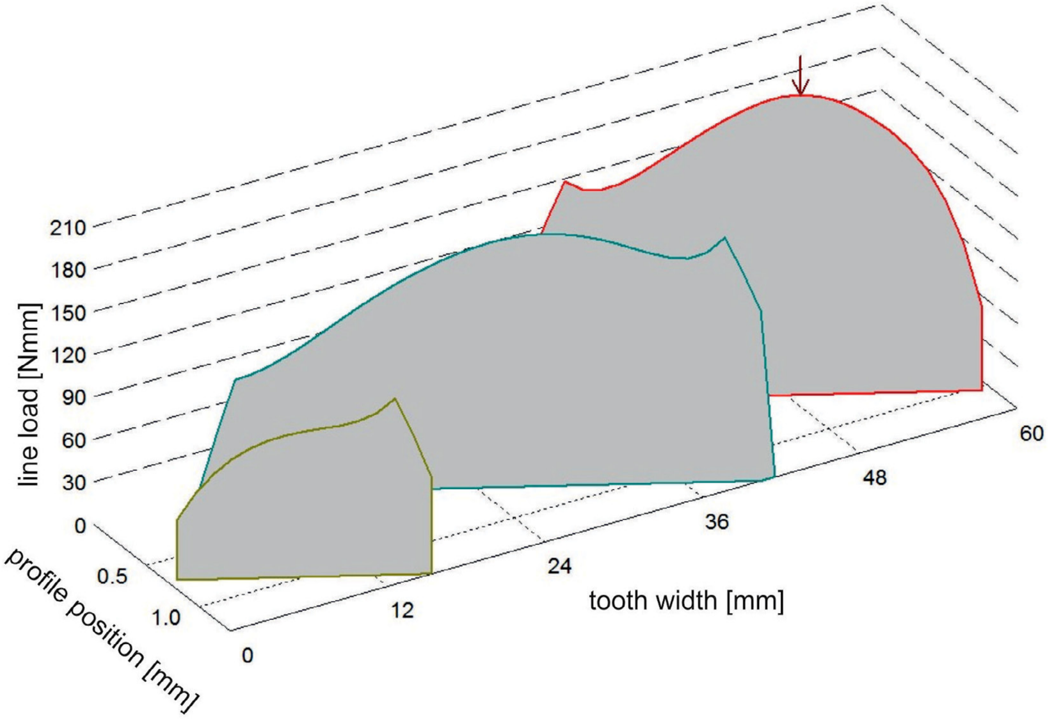

Figure 4: Complex gearing load analysis - load distribution at one meshing position

Based on the load distribution on the flanks at one meshing position it is also possible to figure out the load distribution for the entire field of meshing positions (see figure 5).

3.2 Calculation of relevant kinds of tooth stress

Based on the load distribution on the flanks within the entire meshing field also relevant local tooth stress conditions can be calculated. To calculate the gearing failures pitting and tooth root breakage the local calculation methods according to DIN 3990 are implemented in LVR and BECAL (see figure 6).

Up to now no standardized approach to calculate the risk of flank breakages is available. With respect to this, investigations are carried out within the research project. Hence local flank loads are used to calculate the stress conditions inside the tooth using analytical and numerical approaches (see figure 7). The global tooth stress condition (bending, shear stress, pressure) is calculated by the finite-element-method (FEM). The stress condition directly caused by the tooth contact (Hertzian pressure) is calculated in an analytical

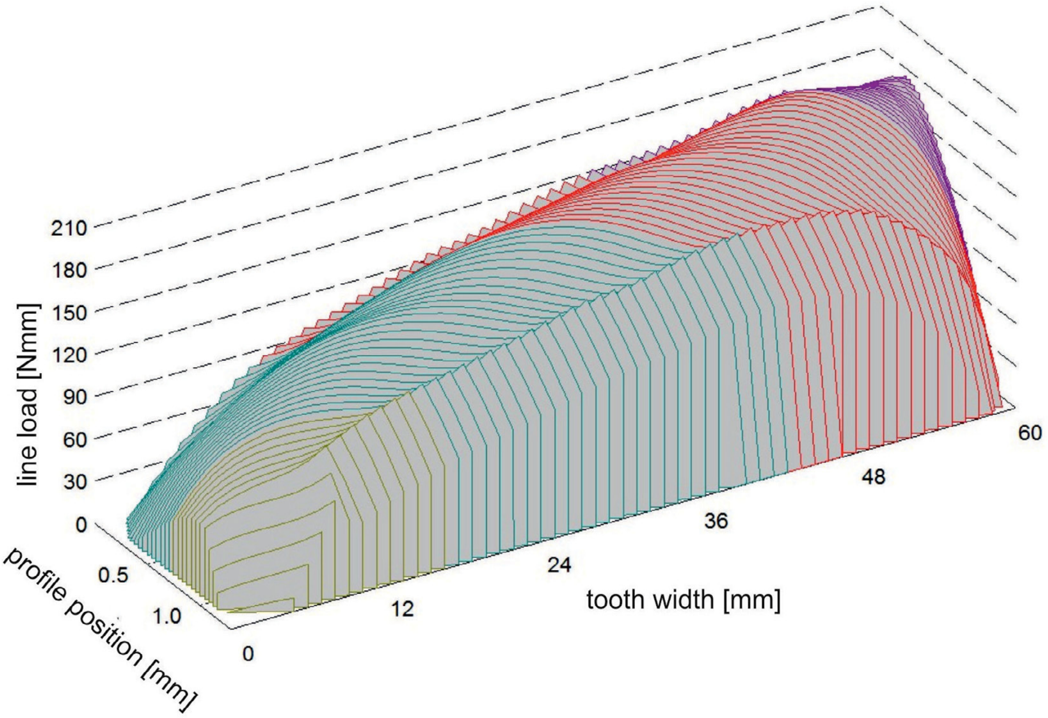

Figure 5: Complex gearing load analysis - load distribution for the entire field of meshing positions

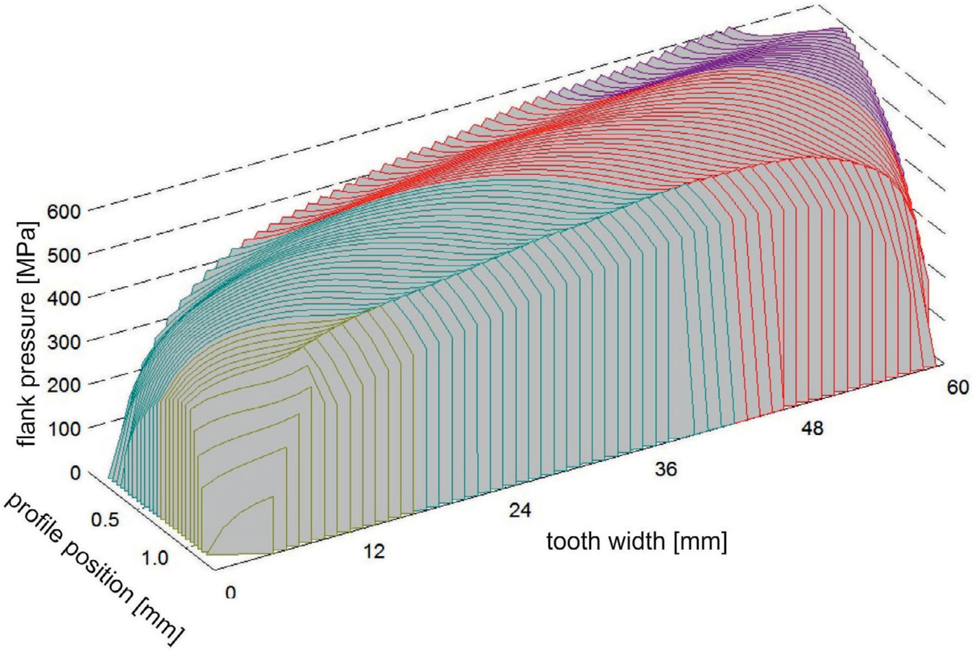

Figure 6: Complex gearing load analysis - distribution of contact pressures

manner, as well as residual stress conditions.

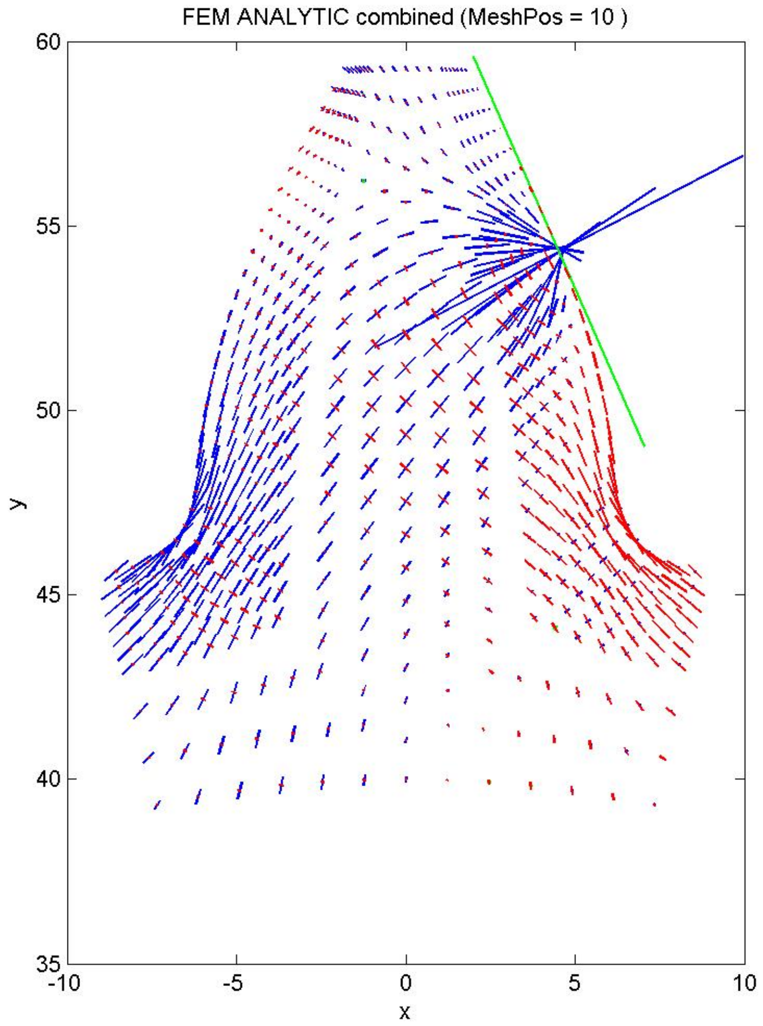

Figure 7: Principal stress inside the tooth by combination of numerical and analytical approaches

3.3 Calculation of the damage rates within the several load-displacement-spectra fields

The calculation of the damage rate of the gearing failures pitting and tooth root breakage is carried out by the mentioned standardized methods. For the calculation of the flank breakage many different approaches are published. Based on these approaches, complemented by own ones, the damage rate is supposed to get calculated for every spectra field. Test runs on a spur and a bevel gear test rig are planned for validation (see figure 8).

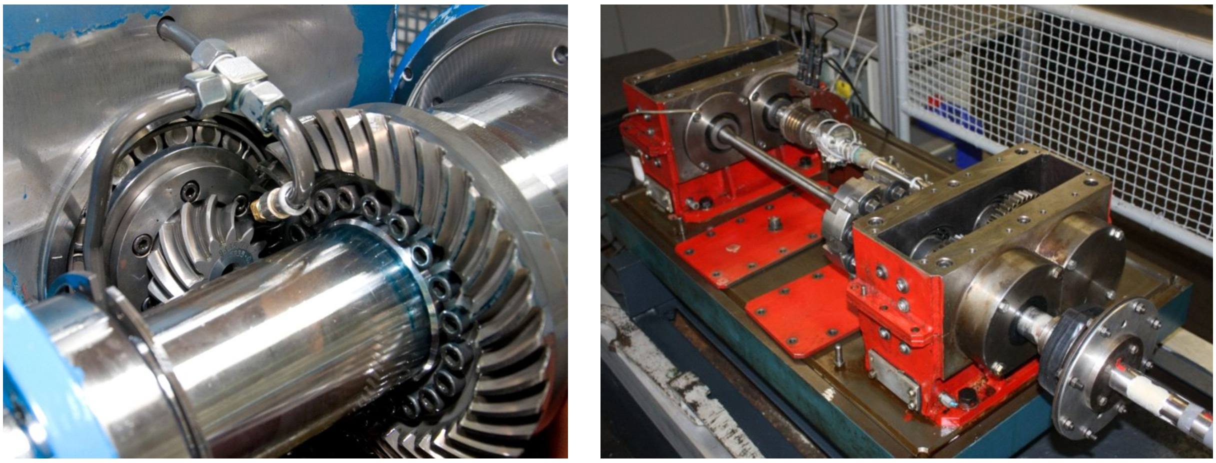

Figure 8: Test rigs - bevel gear (left), spur gear (right)

Listed below is the operating chart for the development of a method to calculate the risk of flank breakages (see figure 9). The best qualified approaches will be adapted on a variety of gearing geometries. If clear tendencies are appearing concerning the risk of flank breakage, some test runs will be performed on these gearings. With this the strength and weaknesses of the different approaches should be revealed as well as the implementation of own thoughts may be realised.

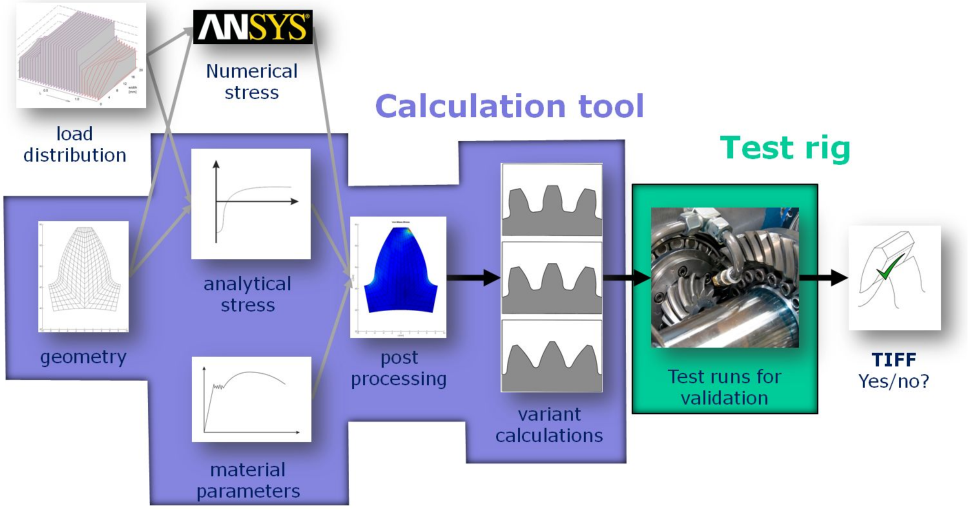

Figure 9: Operating chart for the development of a method to calculate the risk of flank breakage

3.4 Calculation of the total damage sum respectively service life

The several damage rates get collected to a local total damage sum using an appropriate damage accumulation approach. Further on several statements about the local service life in profile and width direction of the flank can be made. This is of importance especially on planetary gear stages with softly mounted or highly loaded planet carriers. Hence the deviation of the flanks is changing during the revolution of the planet carrier. In this case the consideration of the load displacement spectra in combination with the local tooth analysis as presented in this paper offers the possibility of determining appropriate flank modifications and service life statements. This would not be possible with standardised methods.

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