USAGE OF SYNTHETIC GENERATED AND TACTILE MEASURED FLANK MICRO GEOMETRY IN ROMAX AND TE VALIDATION VIA FE SIMULATION AND MEASUREMENT IN A TORQUE TEST RIG

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Fraunhofer IWU

Romax TECHNOLOGY

AGENDA

- introduction
- Why micro geometry analysis?
- micro geometry analysis in RomaxDESIGNER
  - synthetic micro geometry & measurement data
  - import and analysis of micro geometry with undulations
- validation of Romax TE with FE simulation and torque test rig
  - gearing and torque test rig
  - simulation models
  - results
- conclusion and perspective

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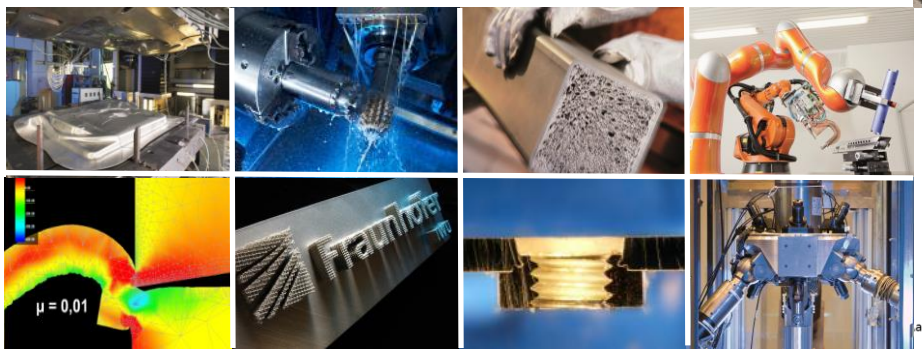
Introduction - The Fraunhofer IWU

Fraunhofer: largest organization for applied research in Europe

- founded in 1991
- about 590 employees
- 37,6 million euro annual budget
- head quarter in Chemnitz, branches in Dresden, Augsburg and Zittau



- fields of expertise

  Machine Tools, Mechatronics, Lightweight Construction, Forming Technologies, Cutting Technologies, Joining and Assembling, Production Management

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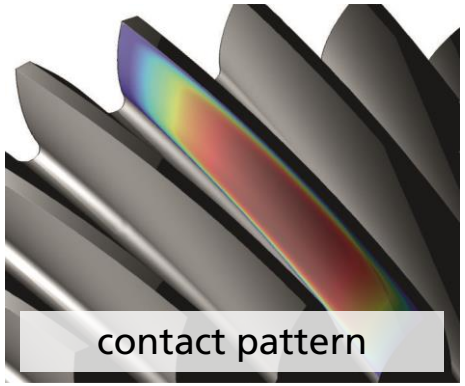
Introduction - Vehicle Technology and Acoustics at IWU

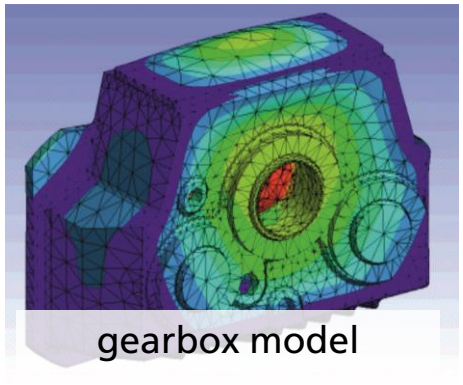
Wide range of expertise, focus on gear noise.

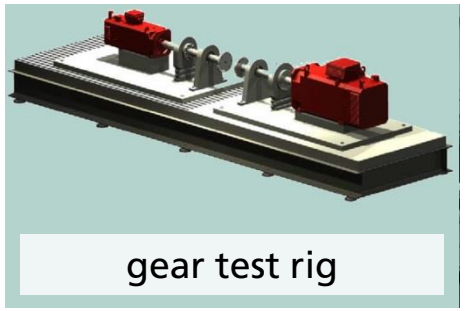
- measurement equipment
  - semi anechoic chamber
  - Laser Scanning Vibrometer
  - shaker test bench
  - acoustic cameras
  - from 2015: transmission test rig
  - etc.
- software
  - RomaxDESIGNER
  - PULSE Reflex Core and LabShop incl. TPA, OTPA, OMA, ODS, etc.
  - FEMtools and ME'scope
  - ANSYS and ABAQUS
  - ITI SimulationX
  - etc.


3d laser vibrometer


car shaker test rig


contact pattern


gearbox model


gear test rig


semi anechoic chamber

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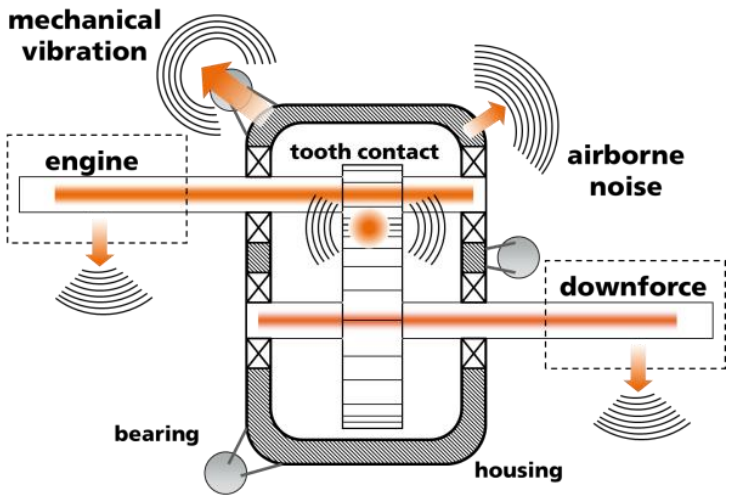
Why Micro Geometry Analysis?

Because it´s of significant relevance for vibration excitation!

- acoustic aspects of the gear box increasingly importat
- reason: missing masking (of combustion engine) in electric powered vehicles.
- tooth contact excitation is main source of noise in gear boxes
- excitation in the tooth contact due to
  - variable contact stiffness
  - deformation and deflection of the gear wheels
  - surface structure
  - reversion of friction force at pitch circle
  - change of relation of overlap due to load (reason for specific modifications)
  - deviations from exact involute geometry



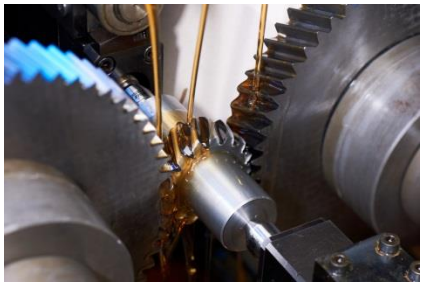
[Linke, H.: Stirnradverzahnung]

Why Micro Geometry Analysis?

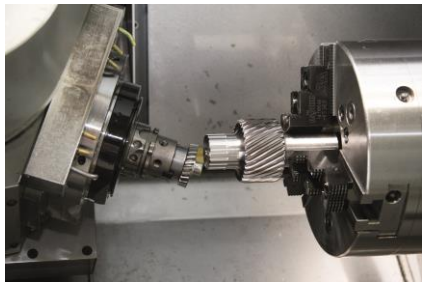
Because it´s affected by manufacturing technology!

- influence of production processes
  - kinematics of gear generation
    - e.g. formation of twist / bias through grinding of crowning
  - geometric deviations, e.g. of the wheel body
    - e.g. wrong orientation of tool or work piece (radial run-out, wobble)
  - dynamic characteristics of production machine in interaction with process forces
    - e.g. formation of small undulations (“ghost frequencies”)
- … synthetic nominal micro geometry sufficient?

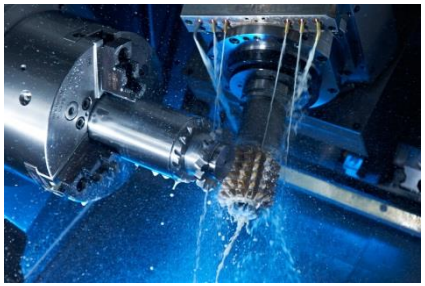
available technologies for gear production at Fraunhofer IWU



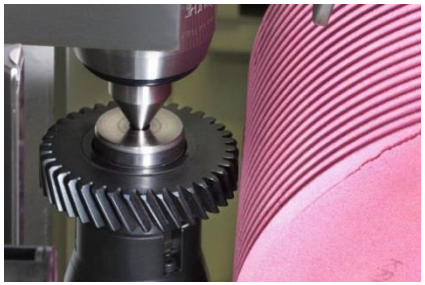
forming



shaving



milling



grinding

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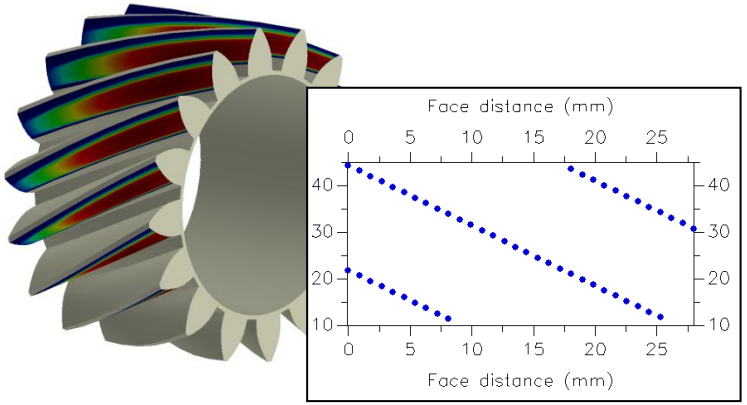
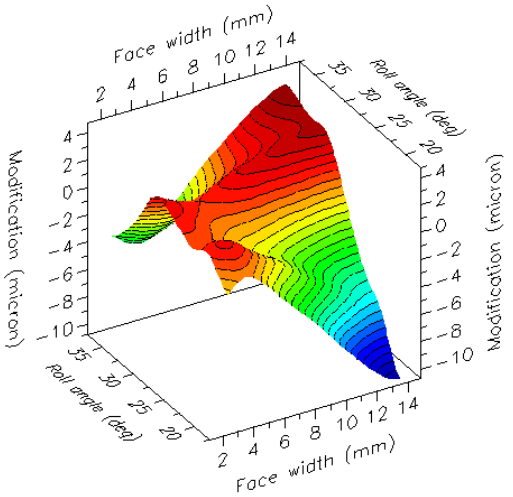
Micro Geometry in RomaxDESIGNER

Available options for generation, import and analysis.

- various options to generate of micro geometry characteristics
  - bias
  - relief (linear / parabolic)
  - slope, crowning, barreling
  - pitch error
- opportunities of analysis and benchmark
  - static and dynamic transmission error (TE)
  - load distribution
  - flash temperature
  - etc.
- import of measurement data
  - matrix of deviations in defined ranges
  - equidistant grid
  - access path for individual generated micro geometry





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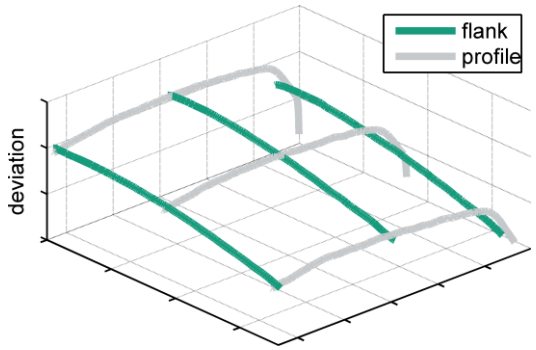
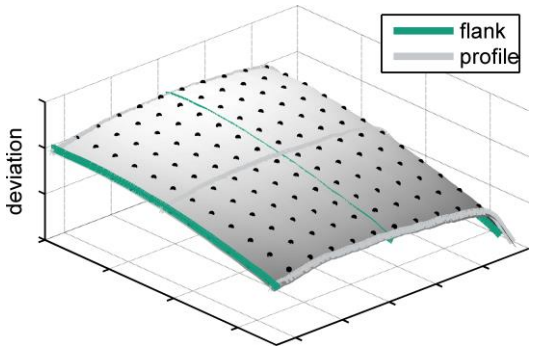
Micro Geometry in RomaxDESIGNER

Analysis of waviness - a variable surface for every single tooth.

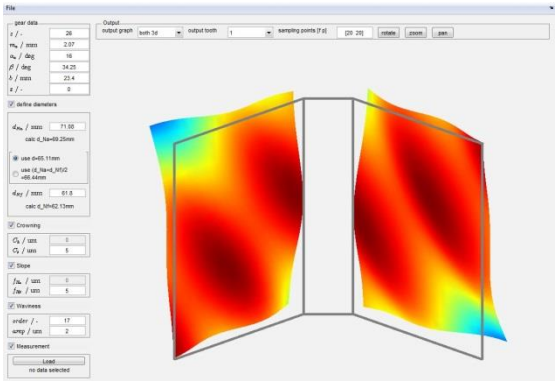
- self-written tools in MATLAB and Excel for synthesis of deviations
- present capabilities (extensible)
  - relief, bias
  - consideration of production induced bias as function of crowning
  - generation of undulations of defined wave length and amplitude
  - import (and optional overlay) of measurement data (currently ZEISS)
  - export of matrix of deviations to RomaxDESIGNER or point cloud to ANSYS



measured lines



interpolated matrix



synthetic flank form deviation

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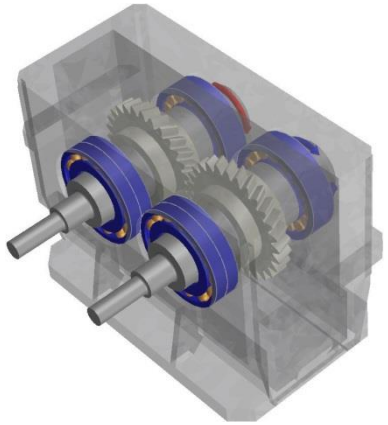
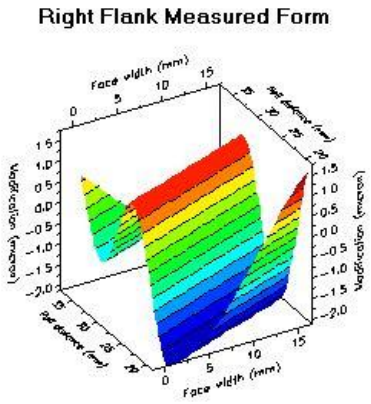
Micro Geometry in RomaxDESIGNER

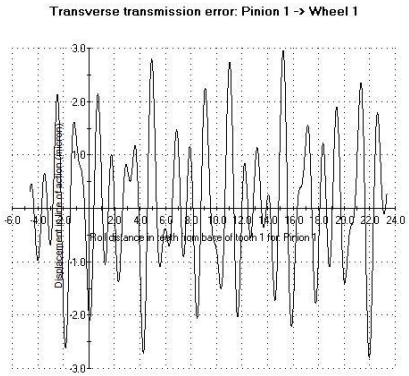
Analysis of waviness - a variable surface for every single tooth.

- specification of undulations: 14th , 19th and 27th order
- workflow in Romax
  - batch import of measurement data matrices (*.csv)
  - micro geometry analysis over all teeth
- results (with very low load)
  - TE shows exactly the imported amplitudes and orders
  - acceleration at output shaft shows orders multiplied with system properties

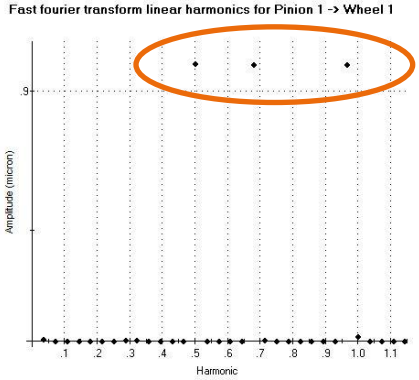




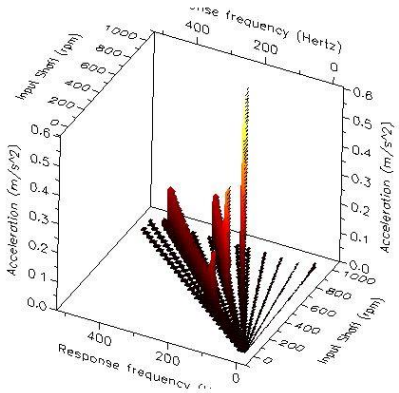
"measured" data



TE over 28 teeth



TE harmonics



acc. at output shaft

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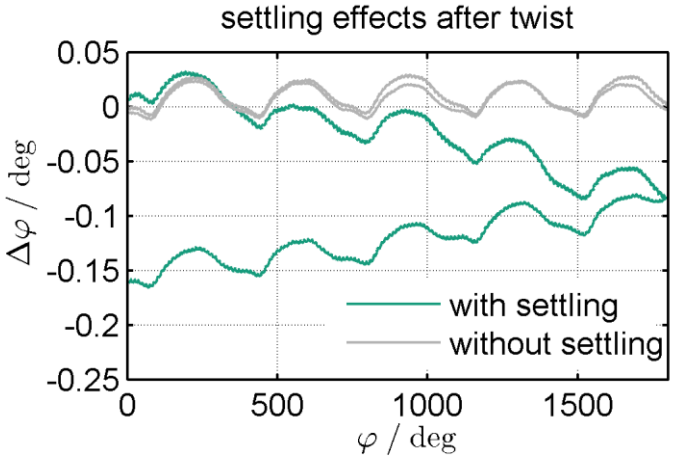
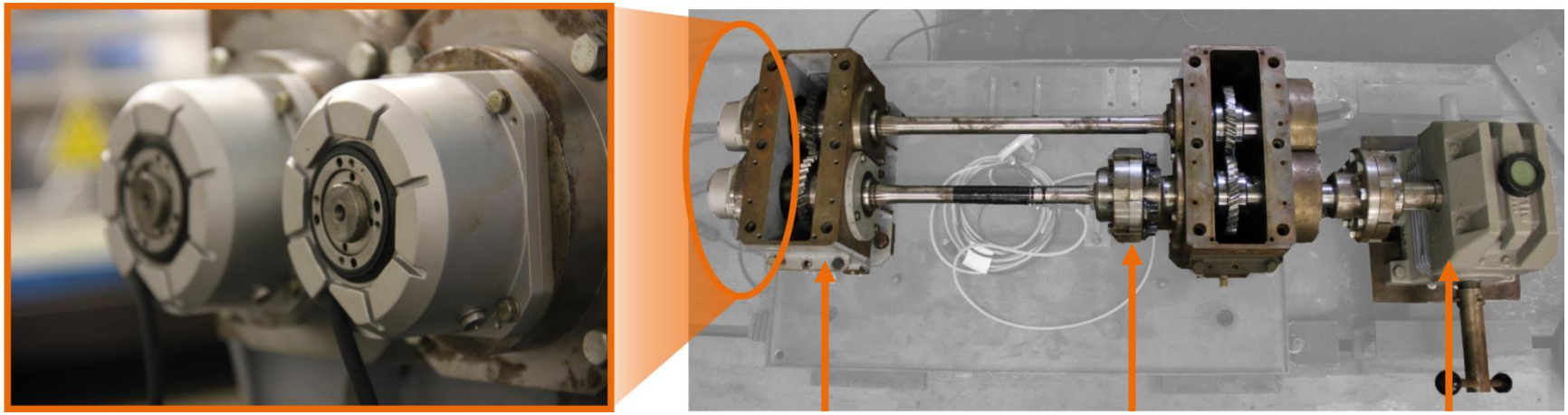
Validation of ROMAX TE – The Torque Test Rig

Parameters of the gearing, measurement method.

- torque test rig
  - quasi-static stiffness identification: below 20 rpm
  - manually driven with worm drive
  - load clutch for different load levels
  - one torsion shaft with torque measuring
  - settling after first twist with load clutch





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Validation of ROMAX TE – The Torque Test Rig

Parameters of the gearing, measurement method.

- gear data and dimension (ideal)
  - centre distance: 125 mm
  - gear ratio: -1
  - profile shift coef.: 0.4888
  - transvers contact ratio: 1.5
  - axial contact ratio: 0.5
  - number of teeth: 28
  - normal module: 4 mm
  - tooth width: 16.3 mm
  - normal pressure angle: 20 °
  - helix angle: 22.7 °

- TE measurement via rotary encoder
  - 2x Heidenhain RON 285
  - system accuracy: ± 5’’
  - division marks: 18000

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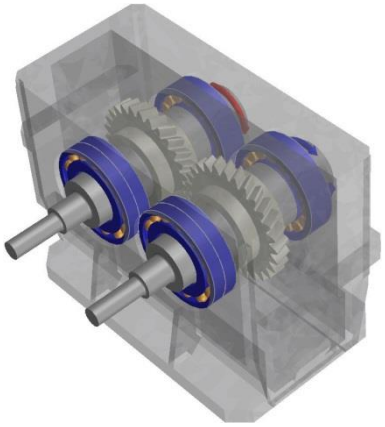
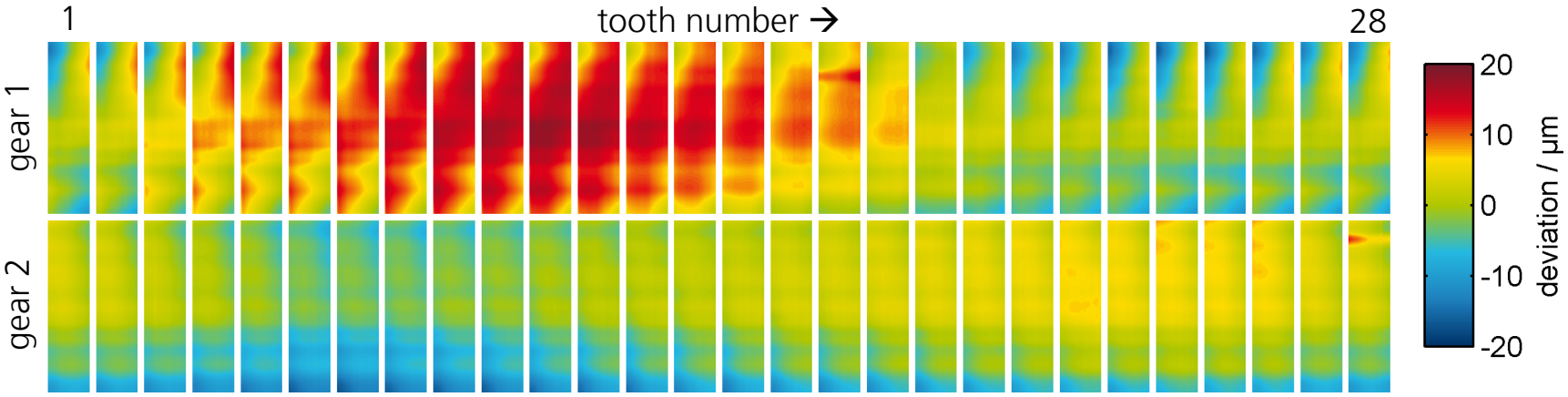
Validation of ROMAX TE – The ROMAX Model

Model Description & Import of Measurement.

- basis: system according to the described torque test rig
- symmetric construction (same shaft geometry and bearings)
- two-shaft system
- bearings per shaft
  - double row radial ball bearing 4212
  - cylindrical roller bearing NU2212
- measured deviation matrices (shown in figure below)
  - left flanks of all teeth





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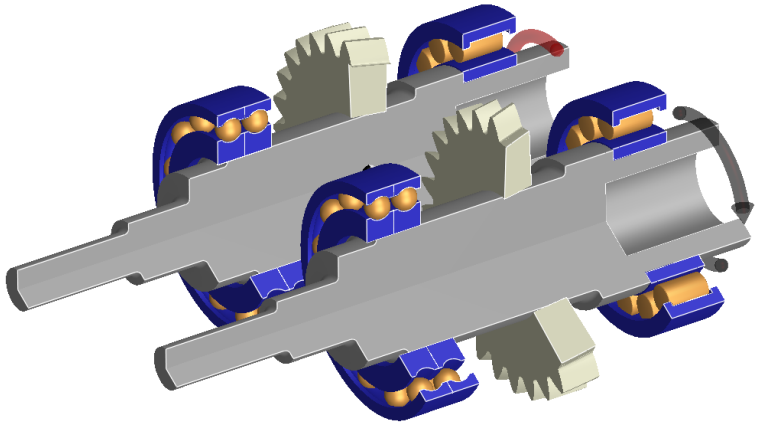
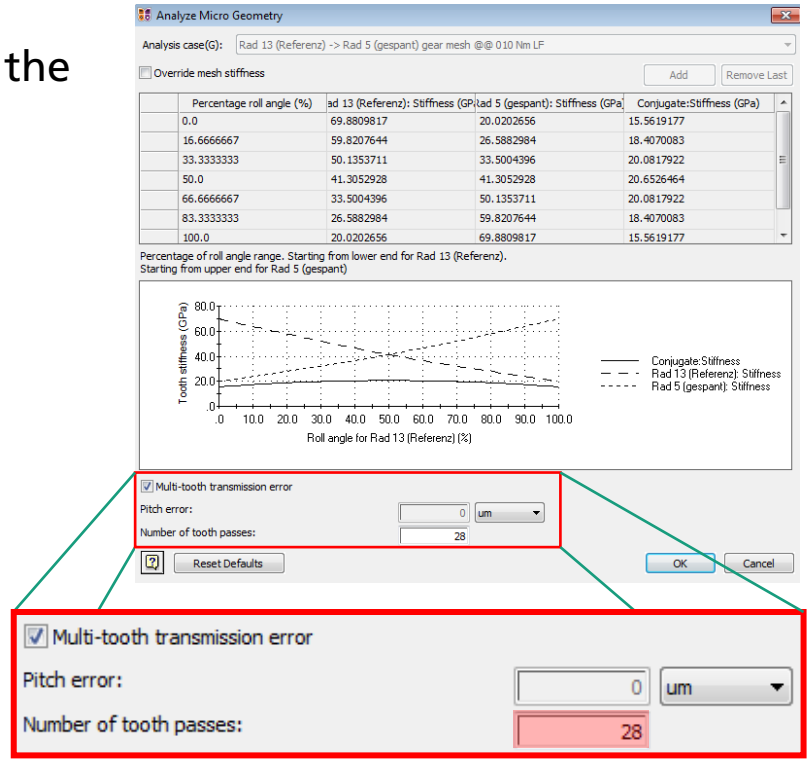
Validation of ROMAX TE – The ROMAX Model

Model Description & Import of Measurement.

- import of all measured flank deviations into Romax using batch import
- required module: Helical Gear Multi Tooth Micro-Geometry Module
- calculation of TE using multi-tooth TE analysis (number of tooth passes equal to number of teeth – in this case 28)
- TE over one complete rotation as well as the corresponding spectrum are the basis for comparison of measurement and simulation





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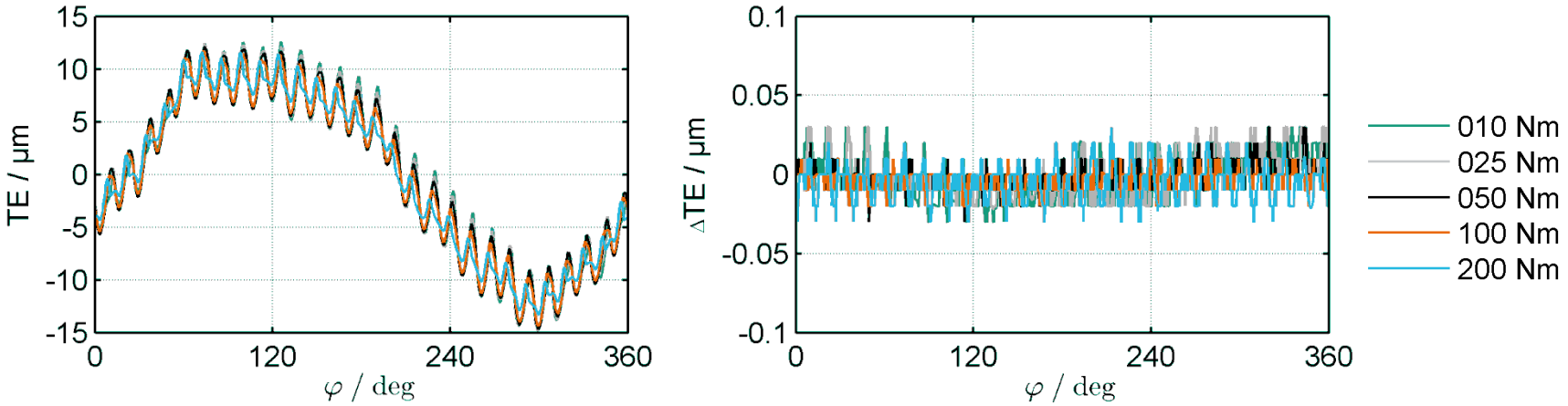
Validation of ROMAX TE – The ROMAX Model

Influences of **Shafts, Bearings, Housing** & Loads.

- consideration of shaft deflections, bearing effects and housing influences
- comparison of two models
  - model 1: no mesh misalignment due to shaft deflections
  - model 2: using calculated mesh misalignment from shaft deflections
- main objective: boundary conditions of FE model
- results of TE calculated by Romax shown below
  - left: significant impact of pitch error
  - right: minimal deviations between the two models at different loads



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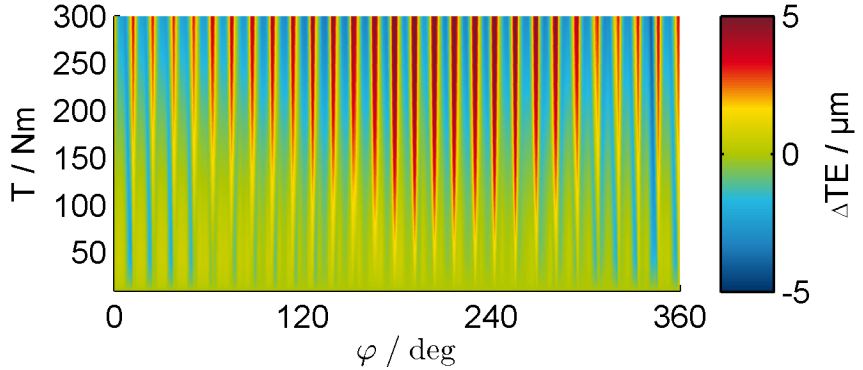
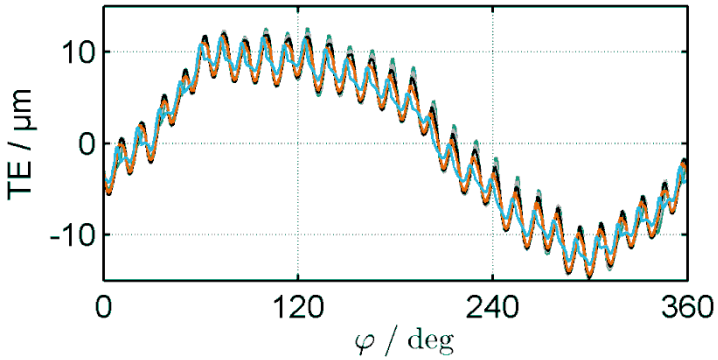
Validation of ROMAX TE – The ROMAX Model

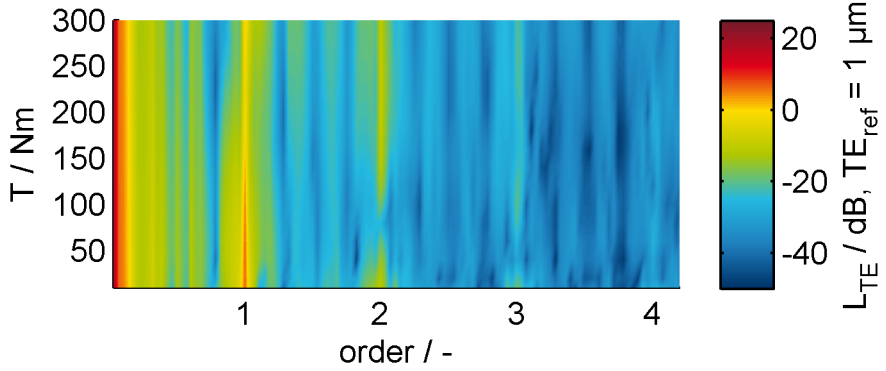
Influences of Shafts, Bearings, Housing & **Loads**.

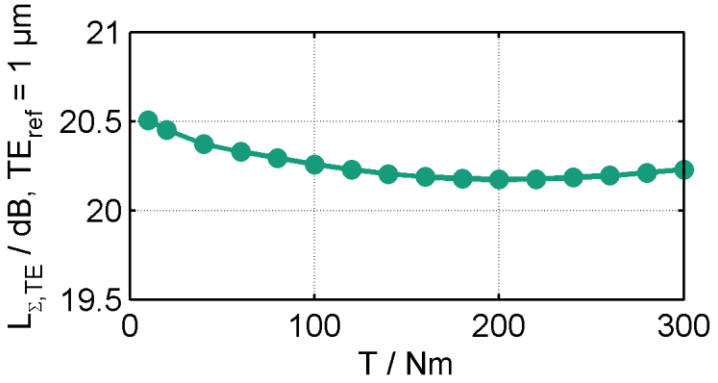
- detailed investigation of the input torque influence
- differences between TE at different loads with reference to T = 10 Nm





- corresponding order spectrum in log. representation and overall level





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Validation of ROMAX TE – The FE Model

Geometry generation, element types, boundary conditions.

- focus: influence of micro geometry on TE
- micro geometry leads to excitation by a displacement → minimization of other excitation mechanisms such as
  - stiffness variation or
  - meshing interference due to load dependant deformation

→ **unloaded** simulation suitable

- gear blank and teeth modelled as rigid bodies
- merely detailed modelling of all flanks
  - import of point cloud generated by MATLAB
  - creation of nodes (on points) and shell elements with linear shape functions
    → shape function with no influence on TE calculation since in **unloaded** simulation only geometrical contact sections will be determined
  - definition of symmetrical contacts
    → necessary because of convex forms of tooth flanks

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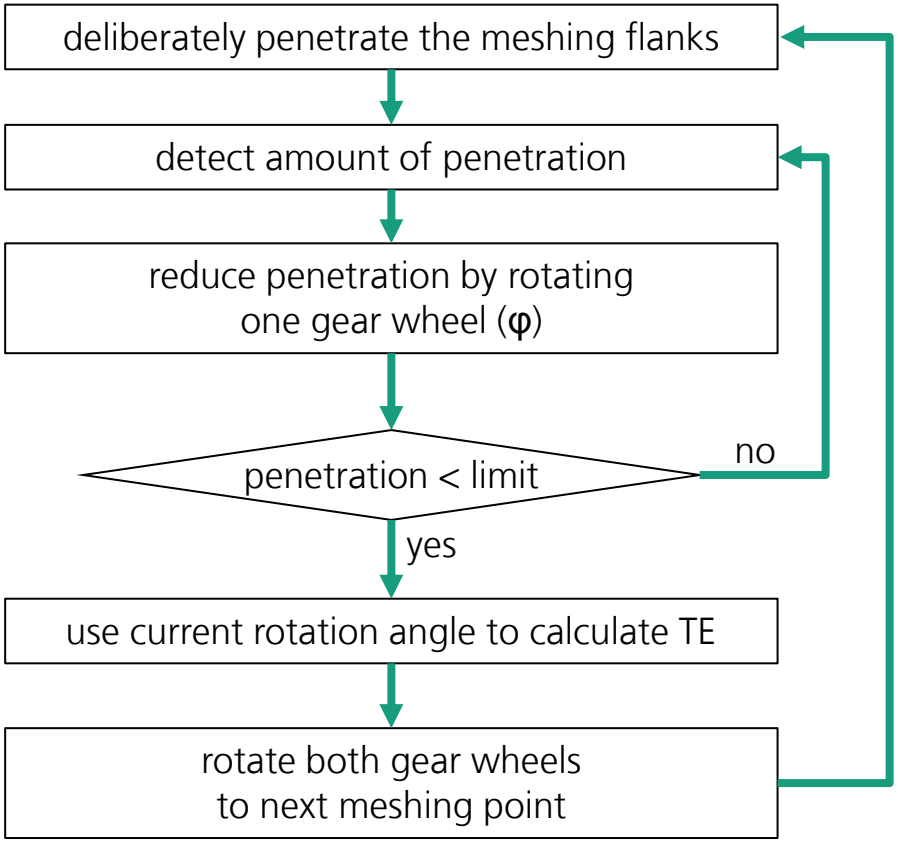
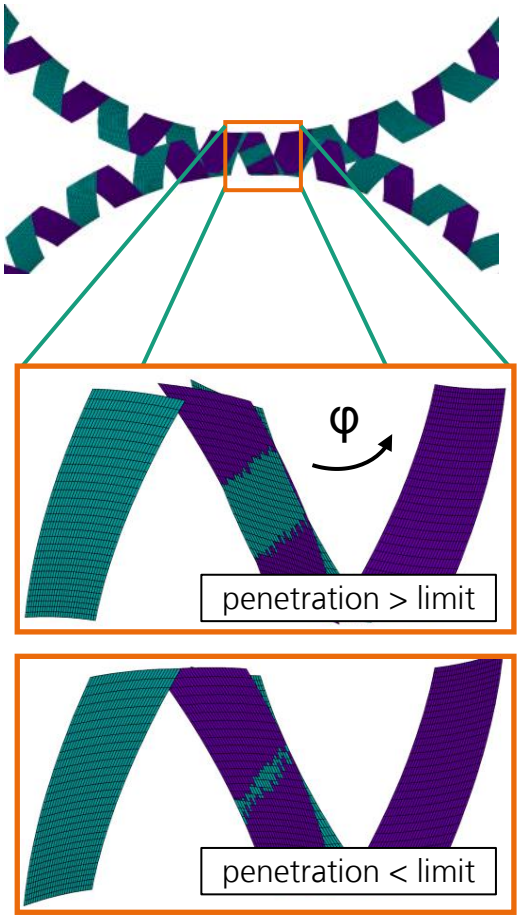
Validation of ROMAX TE – The FE Model

Geometry generation, element types, boundary conditions.

- claim: tooth contact by penetration on flank surfaces
- simulation process in schematic form





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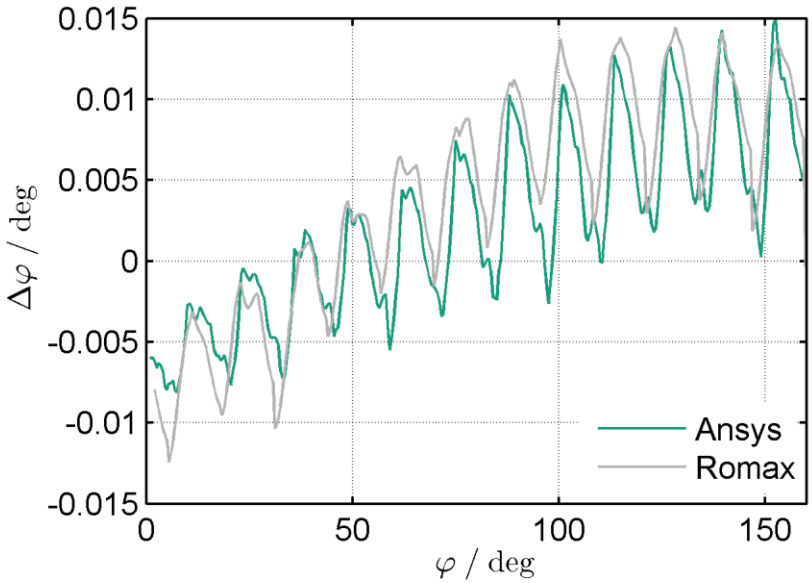
Validation of ROMAX TE

Comparison of FE and Romax TE results.

- comparison of unloaded meshing process only
- same data base (interpolated measurement data) for both calculations
  - same measurement matrix resolution
  - nearly same rotation angle step range (Romax 0.4°, ANSYS 0.5°)

- relatively good match even in teeth dependent details
- pitch in simulated range in FE-model fits with Romax calculation
- no calculation over one whole turn in account of high computing time for the FE model
- need for clarification of differences



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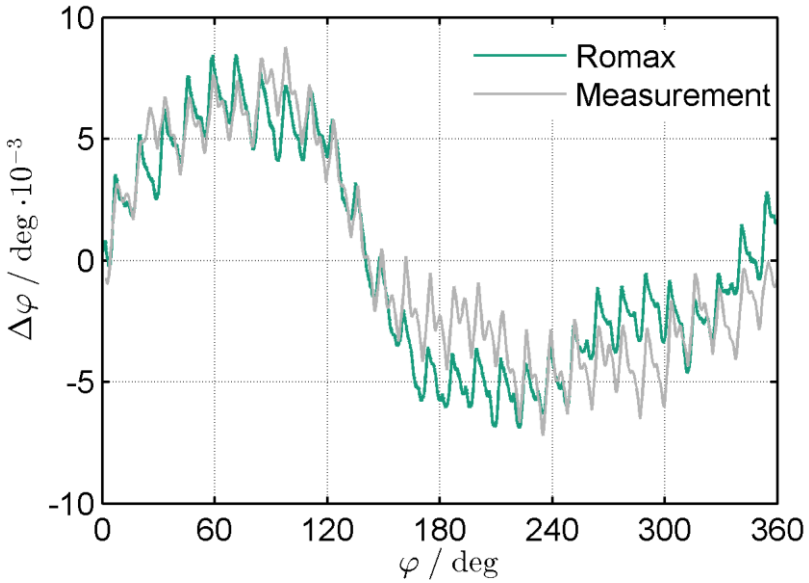
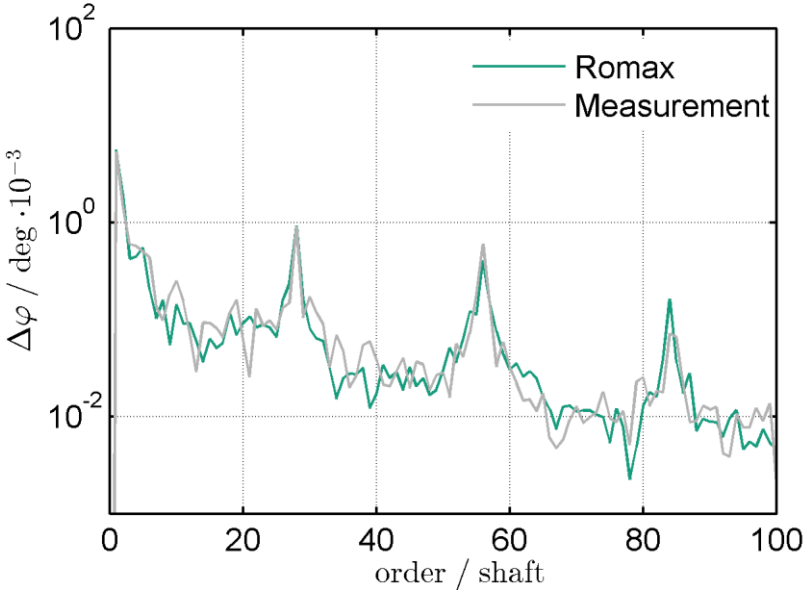
Validation of ROMAX TE

Comparison of picked measurement results.

- Romax shows only slight deviations to the measured pitch error, explainable by influences of the torque test rig and insufficient gear flank measurements (resolution of measurement grid)
- simulated 1st and 2nd (even the 3rd) harmonic of the gear mesh frequency well according to the measurement
- no “ghost frequencies” in this case (finishing by profile grinding)





comparison of measurement and Romax simulation for the right flank at 150 Nm load over a full rotation

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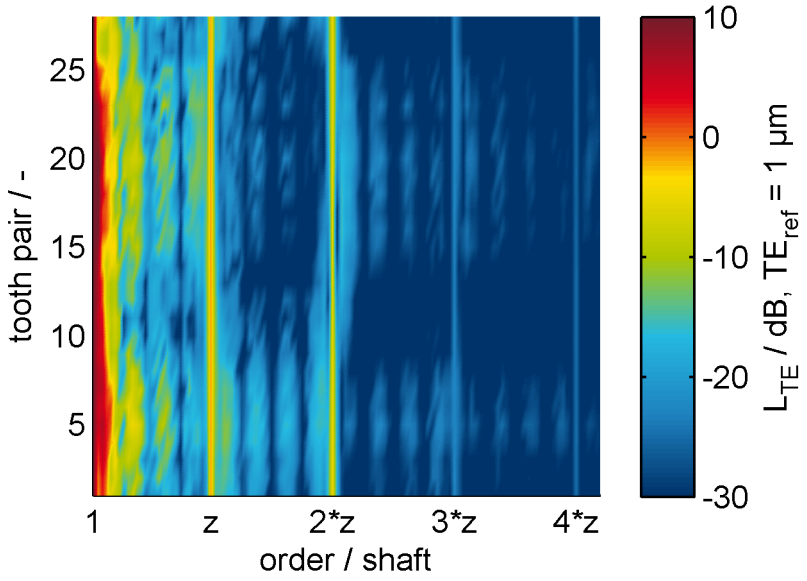
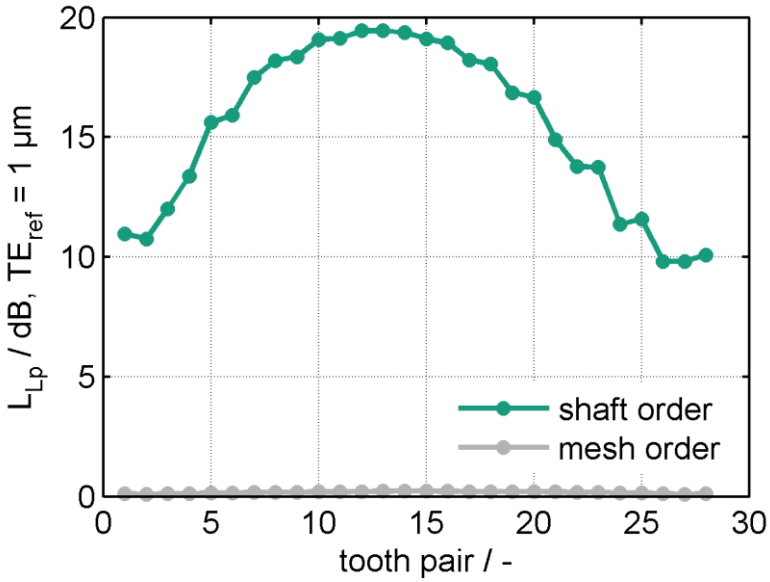
One Exemplary Advantage of ROMAX TE Calculation

Prediction of teeth attribution´s influence.

- TE over one turn for transmission ratio -1 depends on assignment from teeth
  - different TE for meshing of 1st tooth of wheel one with 1st or e.g. 5th tooth of wheel 2
- major influence on first shaft orders
- no remarkable impact on gear mesh order



spectrogram of TE FFT for all 28 teeth assignments



extraction of 1st and 28th order from left figure

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Conclusion and Perspective

Experience regarding micro geometry analysis.

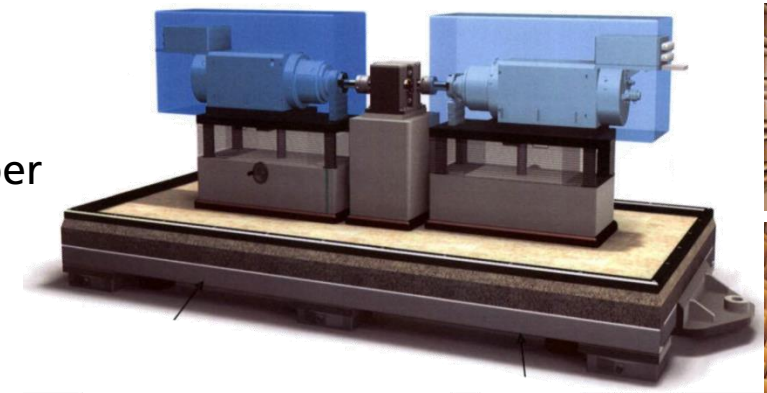
- detailed investigation of teeth micro geometry´s influence on vibration excitation
- significant influence of pitch error identified in this case
- micro geometry affected by production process
- import and analysis of measurement data for every tooth is possible in RomaxDESIGNER
- no influence of the housing, bearings shaft deformation in this case
- TE analysis in Romax shows comparable results to measurement and FE simulation
- very fast analysis over all teeth in Romax: micro geometry analysis over all teeth in several seconds
- FE model extensible for special calculations like e.g. gear blanks with integrated cooling channels or estimation of influence of anisotropy in gear wheel material

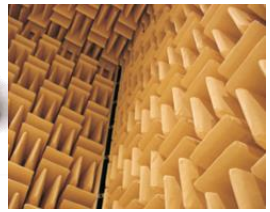
Conclusion and Perspective

What´s next at Fraunhofer IWU with RomaxDESIGNER?

New acoustic test bench at IWU-Dresden (Mid. 2015)

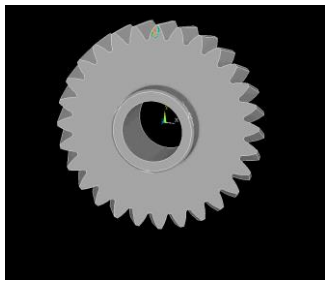
- up to ± 10,000 rpm
- up to ± 1300 Nm
- placed in semi anechoic chamber
- acoustic encapsulated drives
- battery simulator
- validation of Romax models

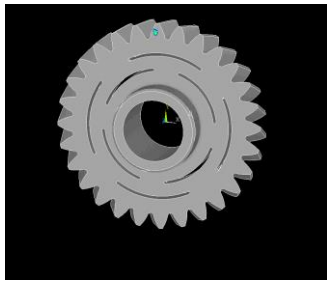




Future investigation in share with Romax and new gear-test bench

- acoustic optimized gear body and it’s stiffness influence into gear meshing
- influence of thermal effects to acoustic behaviour and solidness
- influence of production impacts on micro geometry
- acoustic system influence ranking for high speed electric drives





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Thank you very much for your kind interest.