THERMAL INFLUENCES ON GEAR MICRO GEOMETRY AND ACOUSTIC EXCITATION

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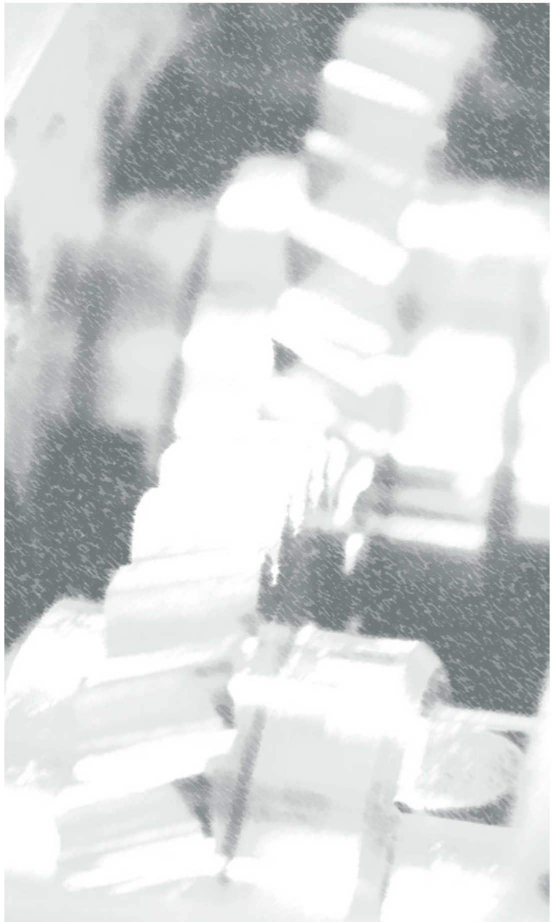
AGENDA

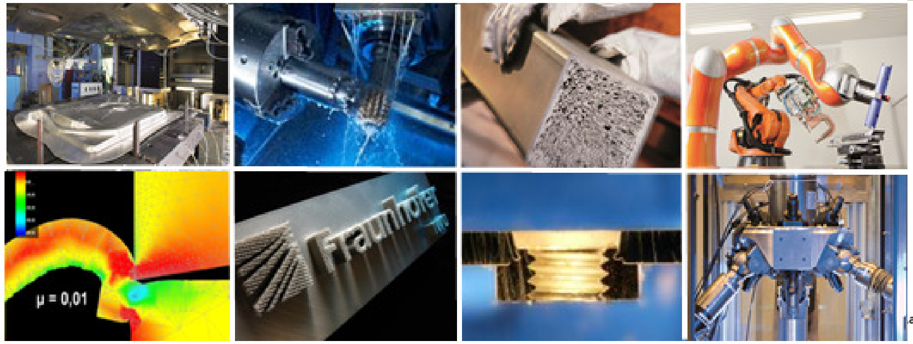
- Introduction
- Why micro geometry analysis?
- Romax batch run approach using MATLAB
  - simple example model
- Calculation of thermal induced change of gear geometry
  - theoretical descriptions
  - batch run model
  - simulation results
- Conclusion and perspective

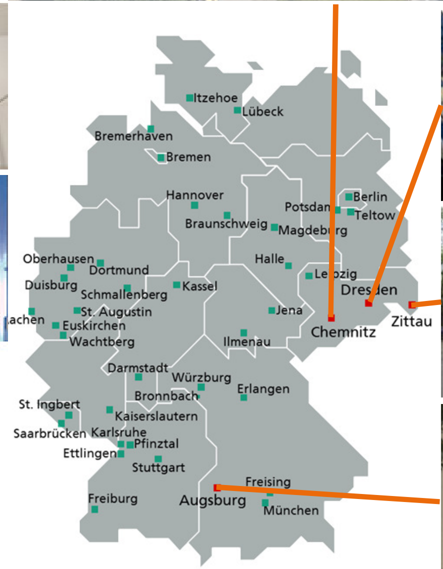


Introduction – The Fraunhofer IWU

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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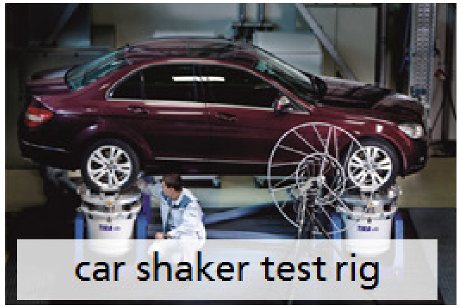
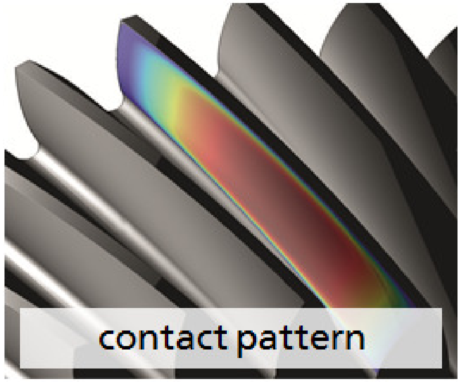
Introduction – Tech. Acoustics and Structural Dynamics

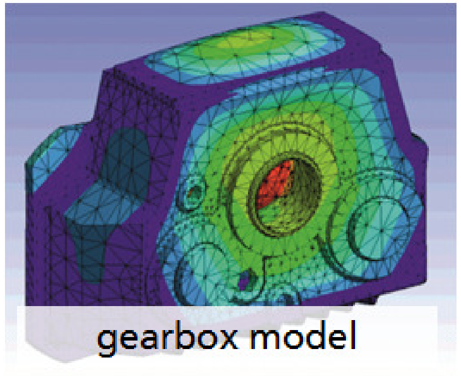
Wide range of expertise, focus on gear noise.

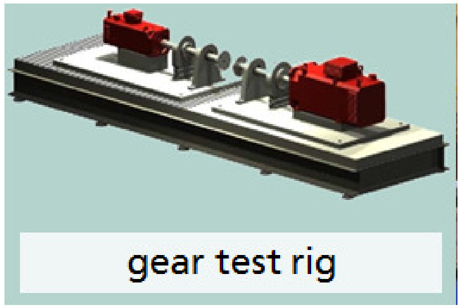
- measurement equipment
  - semi anechoic chamber
  - laser scanning vibrometer
  - shaker test bench
  - acoustic cameras
  - from 2015: transmission test rig
  - etc.
- software
  - RomaxDESIGNER
  - PULSE Reflex Core and LabShop incl. TPA, OTPA, OMA, ODS, etc.
  - FEMtools and ME'scope
  - ANSYS and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

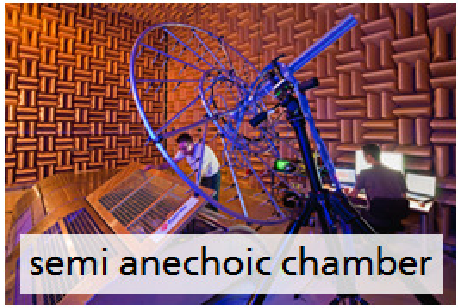

3D laser vibrometer


car shaker test rig


contact pattern


gearbox model

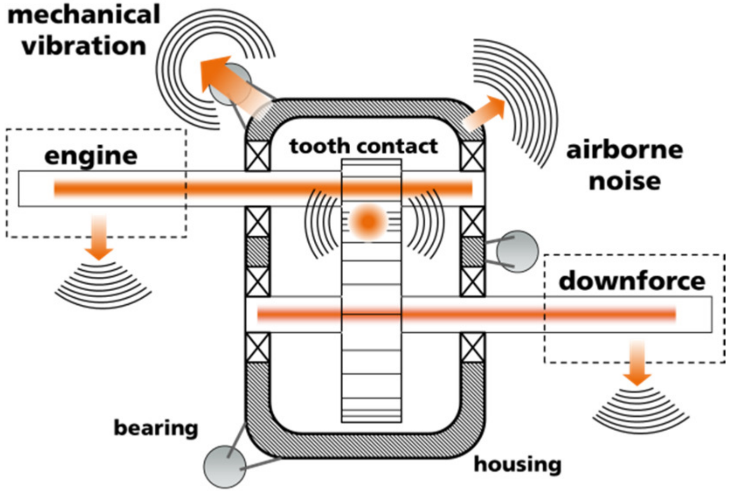

gear test rig


semi anechoic chamber

Why Micro Geometry Analysis?

Because it´s of significant relevance for vibration excitation!

- acoustic aspects of the gear box increasingly important
- 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



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Romax batch run approach using Matlab

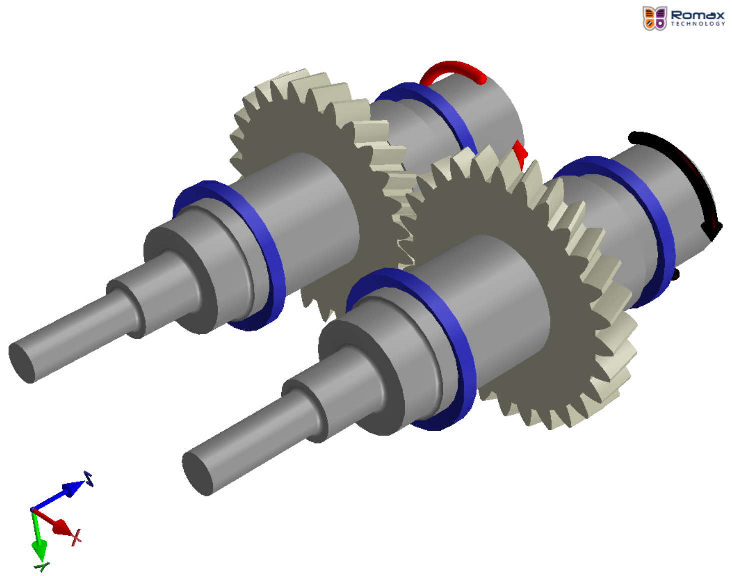
How to use the benefit of both worlds?

- example model
  - single stage gearbox
  - focus on gear mesh → no consideration of peripheral effects (shaft deflections etc.)

- variation parameter
  - input torque
  - limits: 10 Nm to 1000 Nm (increment 10 Nm)

    →101 simulation steps

- result parameters
  - 1st harmonic of TE
  - 2nd harmonic of TE
  - 3rd harmonic of TE



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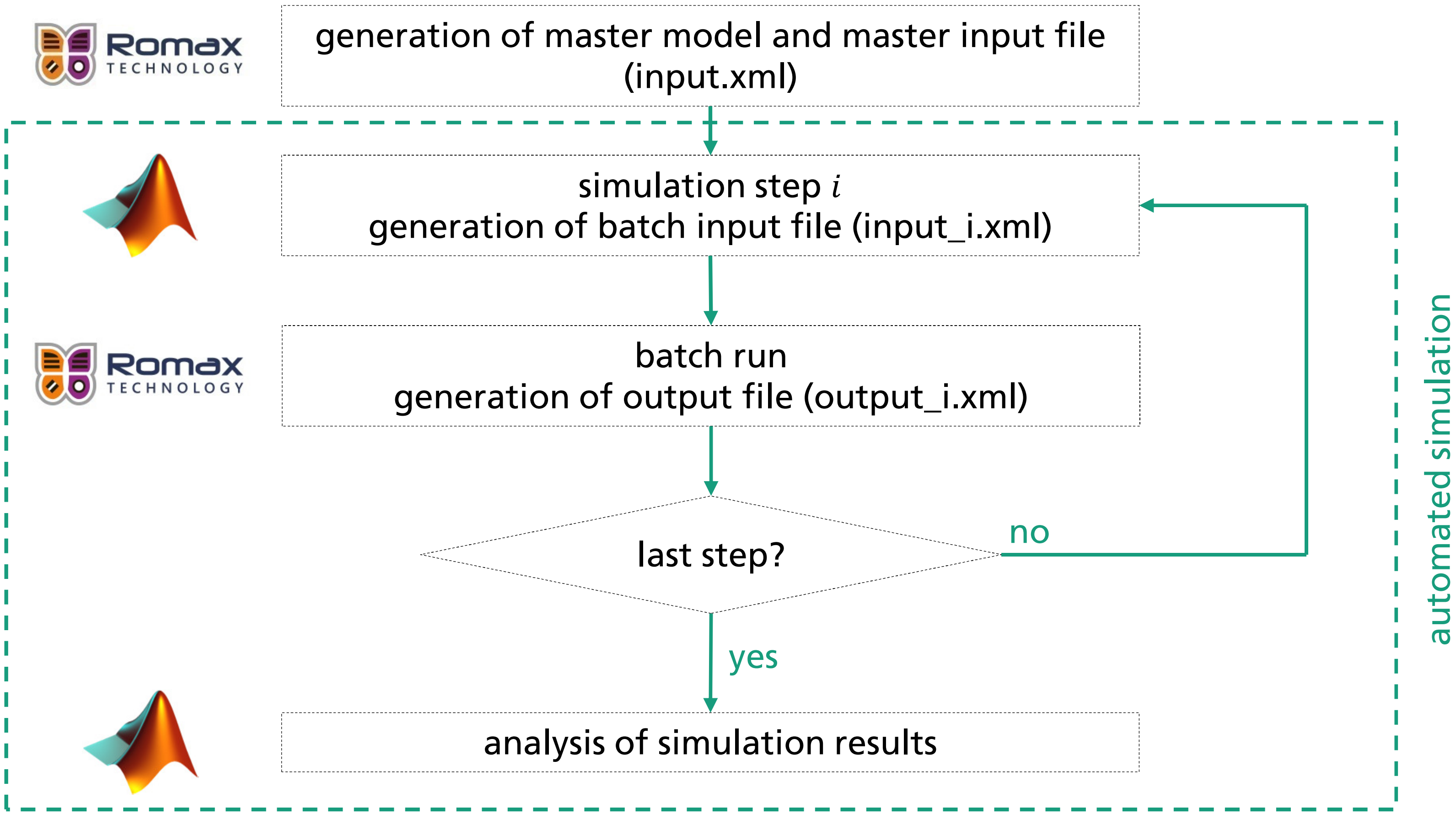
Romax batch run approach using Matlab

How to use the benefit of both worlds?

- simulation process in schematic form



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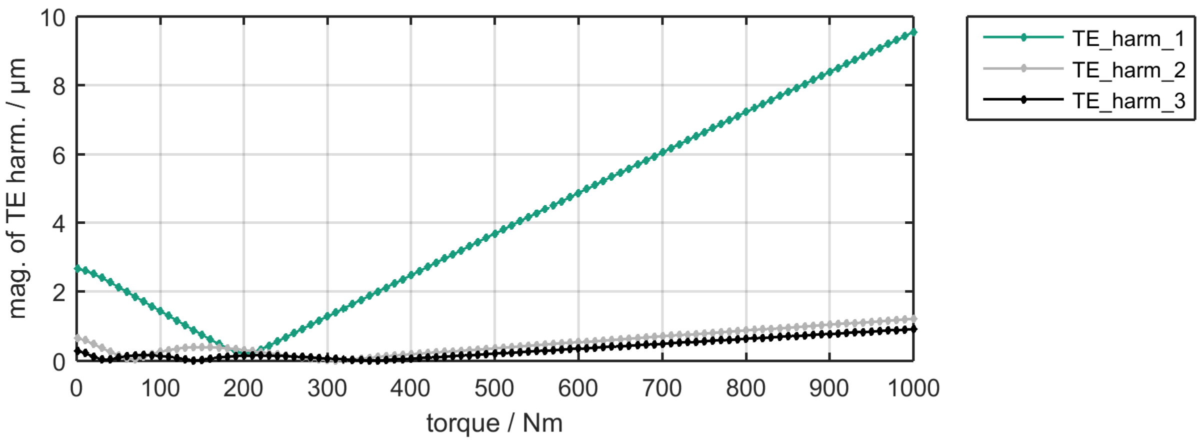
Romax batch run approach using Matlab

How to use the benefit of both worlds?

- example model: simulation duration for 101 load steps about 200 s

```
%% fcn
inpDir = sprintf('%s\\input_files',workDir);
outDir = sprintf('%s\\output_files',workDir);
if ~exist(inpDir,'dir'), mkdir(inpDir); end
if ~exist(outDir,'dir'), mkdir(outDir); end
if batchRunFlag==1
    % start server mode
    command = [ '"C:\Program Files (x86)\RomaxSoftware\RomaxDesigner 14.7.0 Build 58\winrxd.exe"',...
                ' -startAsServer 5555 ',...
                '"C:\Program Files (x86)\RomaxSoftware\RomaxDesigner 14.7.0 Build 58\serverlog.log"'];
    system(sprintf('%s & ',command))
    % batch
    for n0=1:length(T_in)
        clear inpXML
        % write input
        inpXML = xmlread(fullfile(workDir,'input.xml'));
        allCase = inpXML.getElementsByTagName('Case');
        for n1=0:allCase.getLength-1
            allCaseItems = allCase.i
            ACI_variables = allCase
            if ACI_variables.getLeng
                for n2=0:ACI_variabl
```

batch mode



Thermal induced geometry change

Calculation and Modelling.

- bibliographical reference
  - Kashyap, S.: *Development of a procedure to describe plastic gear geometry after a temperature change with application to the prediction of gear load distribution.* Master Thesis, Ohio State University, 2011
- assumption: linear thermal expansion (isotropic material behaviour)
- 2 methods
  - temperature influence modelled by change of module $m = f(\Delta T)$
  - temperature influence modelled by change of pressure angle $\alpha_t = f(\Delta T)$
- approach based on base diameter

$$d_b = \frac{z \cdot m_n}{\cos\beta} \cdot \cos\alpha_t$$

- calculation of resultant diameters after temperature increase

$$d_y^{T_1} = d_y^{T_0} \cdot (1 + \alpha_{therm} \cdot \Delta T)$$

- change of tooth thickness analogous

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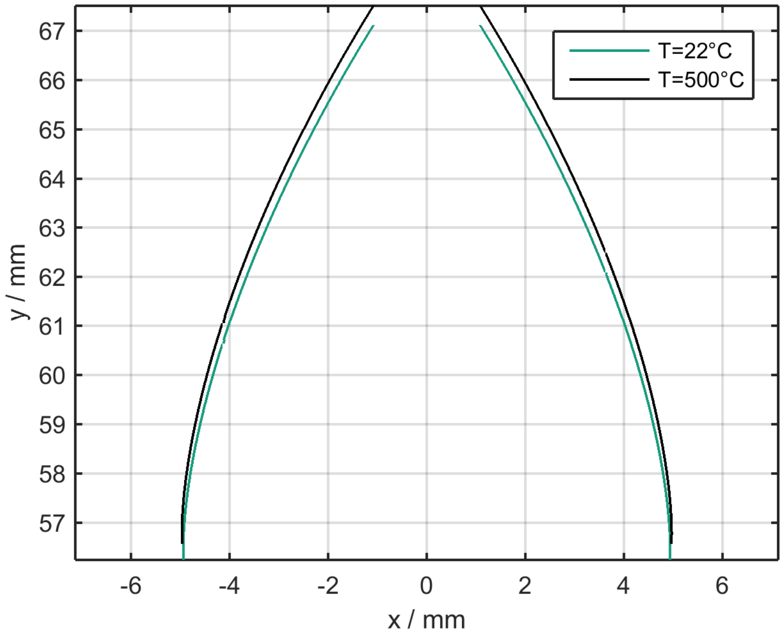
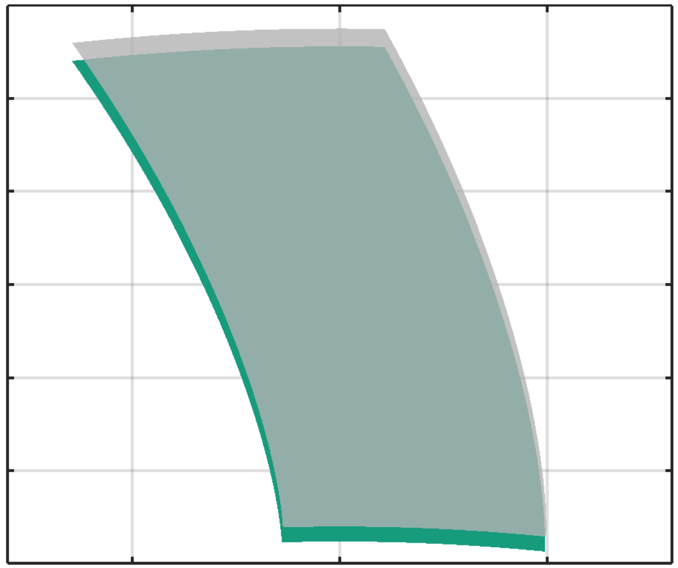
Thermal induced geometry change

Calculation and Modelling.

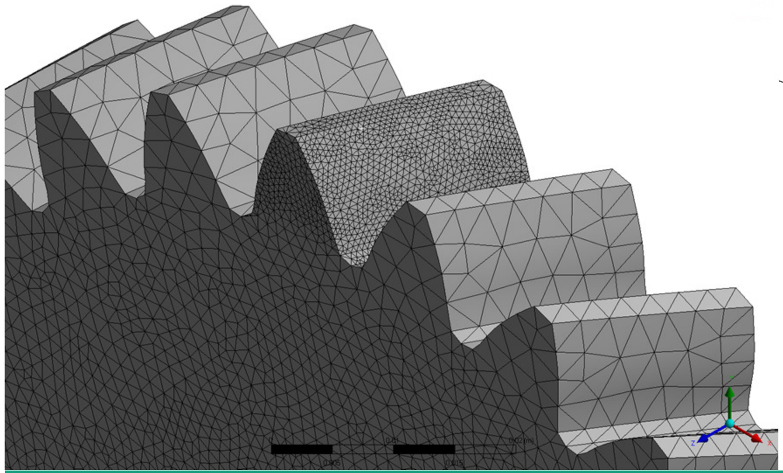
- both approaches with same results
- use of module change
- implementation in MATLAB
  - calculation of gear geometry after temperature rise and output of changed gear parameters

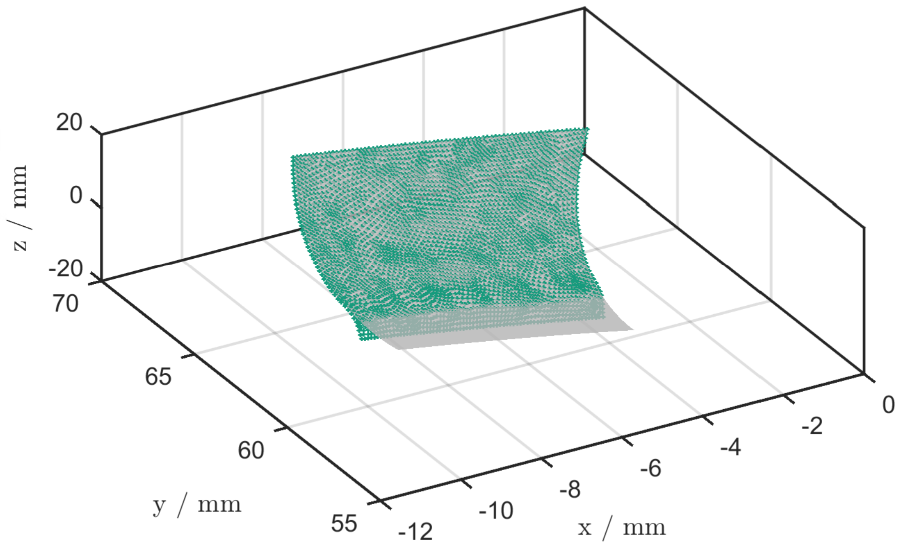




Thermal induced geometry change
Calculation and Modelling.

- validation of analytical model via FE based simulation (ANSYS)
- comparison of analytic calculated tooth flank and numeric determined node displacements
- validation BCs (results shown in figures below)
    - calculation for a temperature rise from 22°C up to 500°C





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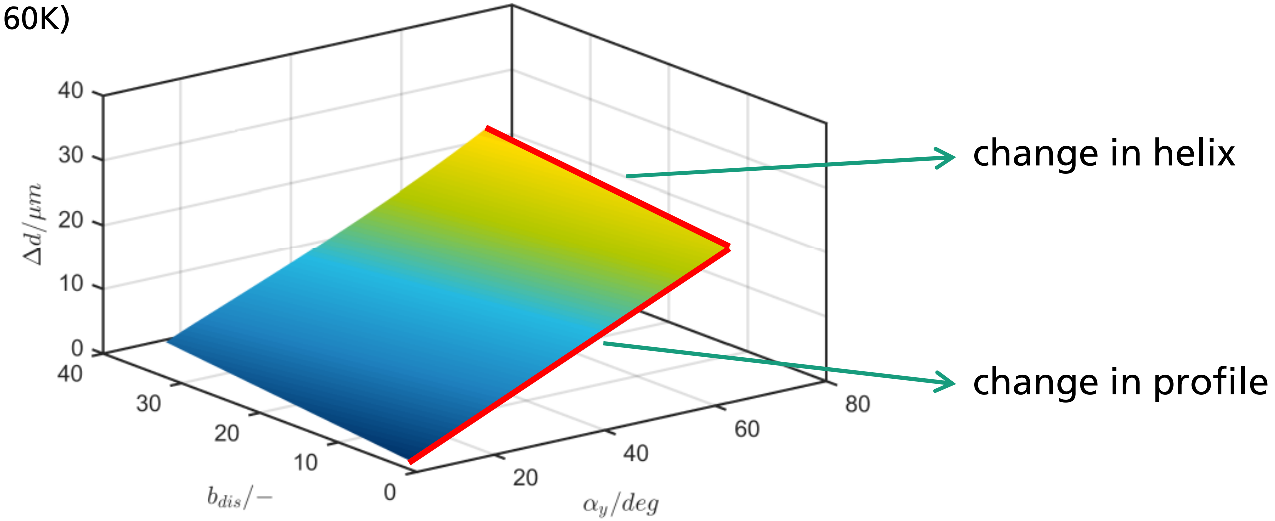
Thermal induced geometry change

Calculation and Modelling.

- investigation of micro geometry change
  - distance of discretised target geometry to analytical actual geometry
- superposition of involute and lead slope (reasonable due to based equations)

$$\boldsymbol{p}(\boldsymbol{\alpha},\boldsymbol{\zeta},r_b,\phi_b,\beta_b) = \begin{bmatrix} \frac{r_b}{\cos\boldsymbol{\alpha}} \cdot \cos(\phi_b + \frac{\tan\beta_b}{r_b}\boldsymbol{\zeta} + f\cdot \mathrm{inv}\,\boldsymbol{\alpha}) \\ \frac{r_b}{\cos\boldsymbol{\alpha}} \cdot \sin(\phi_b + \frac{\tan\beta_b}{r_b}\boldsymbol{\zeta} + f\cdot \mathrm{inv}\,\boldsymbol{\alpha}) \\ \boldsymbol{\zeta} \end{bmatrix}$$

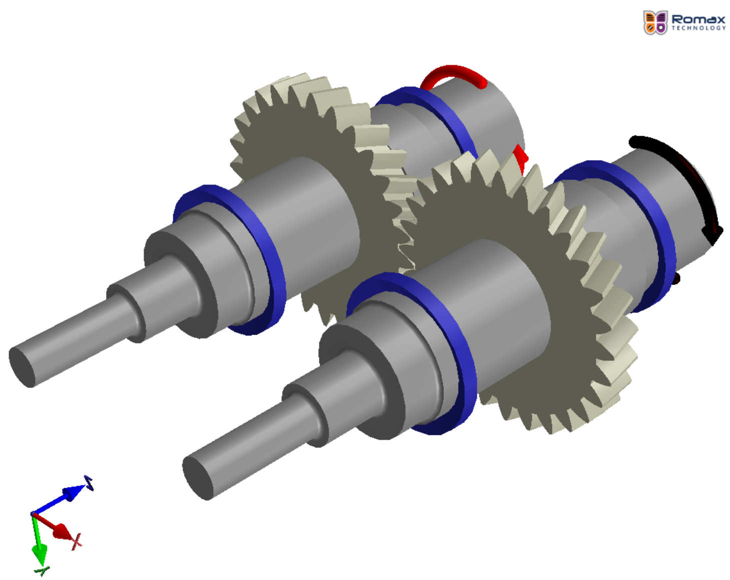
distance: actual to target geometry
(ΔT = 60K)



Thermal induced geometry change

Calculation and Modelling.

- focus on gear mesh
- deflections due to displacements of other components (e.g. deflections due to shaft bending) not considered
- calculation of gear geometry at temperature T_i in MATLAB
- inputs for batch run
  - normal module
  - tooth thickness
  - face width
  - tip diameter
  - root diameter



- comparison of results for randomly chosen gear sets and temperatures with R14.6 (cause of usage of beta release)
  → same results

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Thermal induced geometry change

Calculation and Modelling.

- investigation of 14 different gear sets with various gear geometries
- different parameter ranges

parameter	minimum	maximum
normal module / mm	2	8
face width / mm	16	90
normal pressure angle / deg	15	25
helix angle / deg	0	32
centre distance / mm	77	360
transverse contact ratio / -	1.04	2.06
axial contact ratio / -	0	1.96

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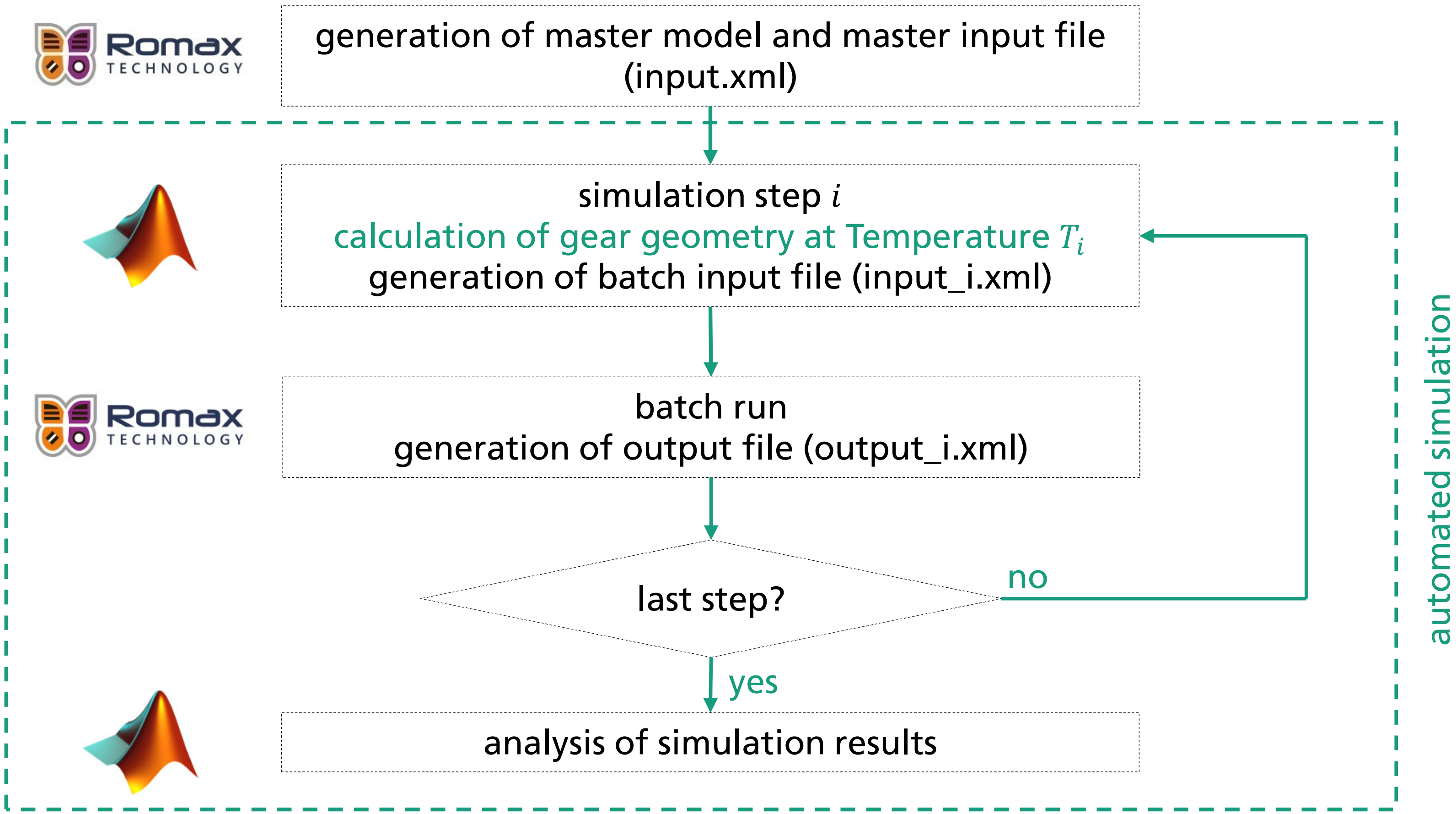
Thermal induced geometry change

Calculation and Modelling.

- changes of simple model necessary



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Thermal induced geometry change

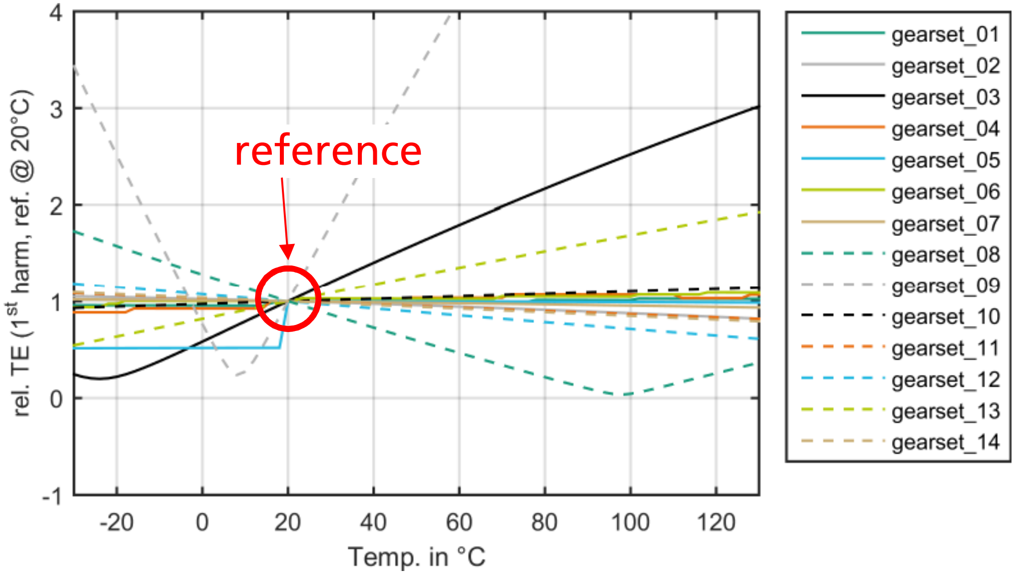
Simulation results.

- objective
  - analysis of change in TE due to temperature variation
- normalization of evaluation parameters x to reference value at 20°C

$$\tilde{x}(T_i) = \frac{x(T_i)}{x(T_{20})}$$

- result parameters
  - 1^{st} harmonic of TE
  - 2^{nd} harmonic of TE
  - 3^{rd} harmonic of TE

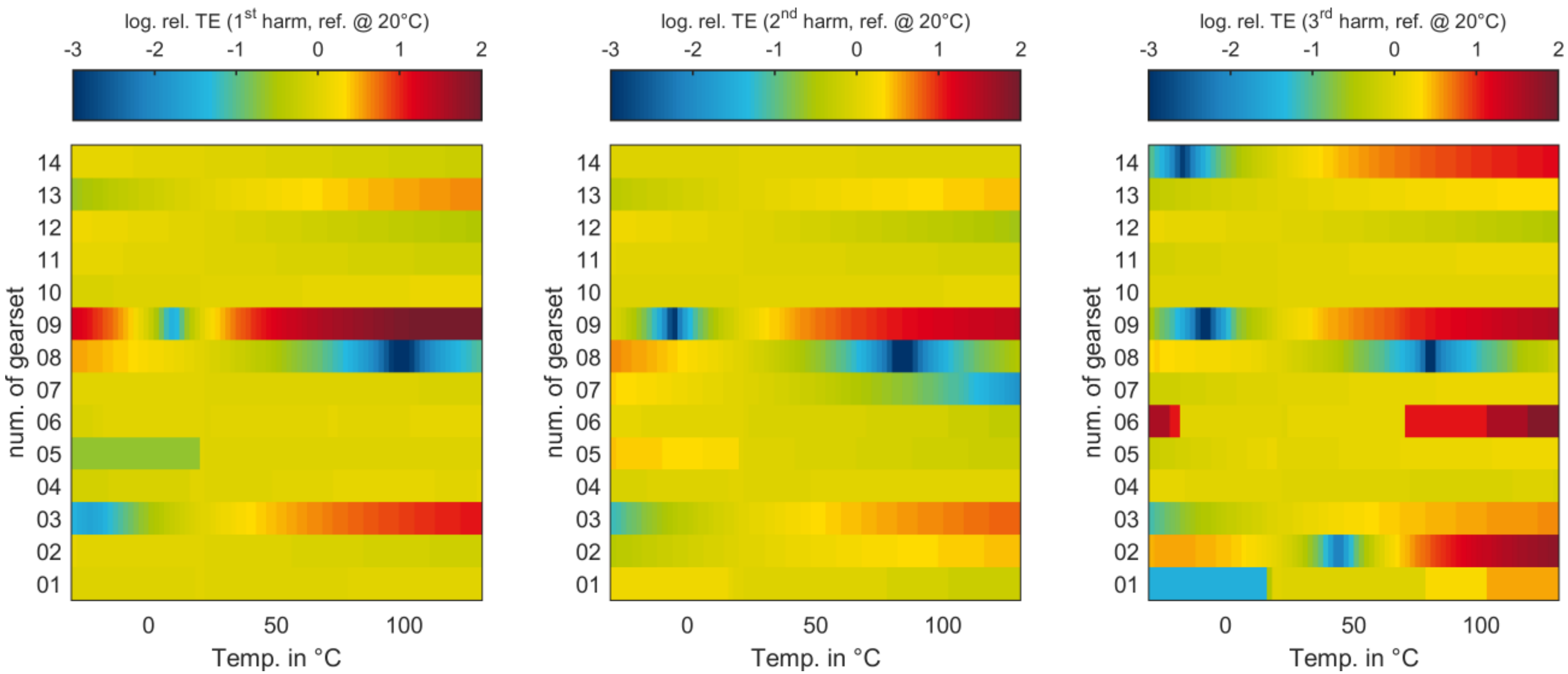
- main focus on 1^{st} and 2^{nd} harmonic



Thermal induced geometry change

Simulation results.

- comparison of TEs for different temperatures and gear geometries
- logarithmic scale due to visualisation
- some gear sets with significant thermal influences



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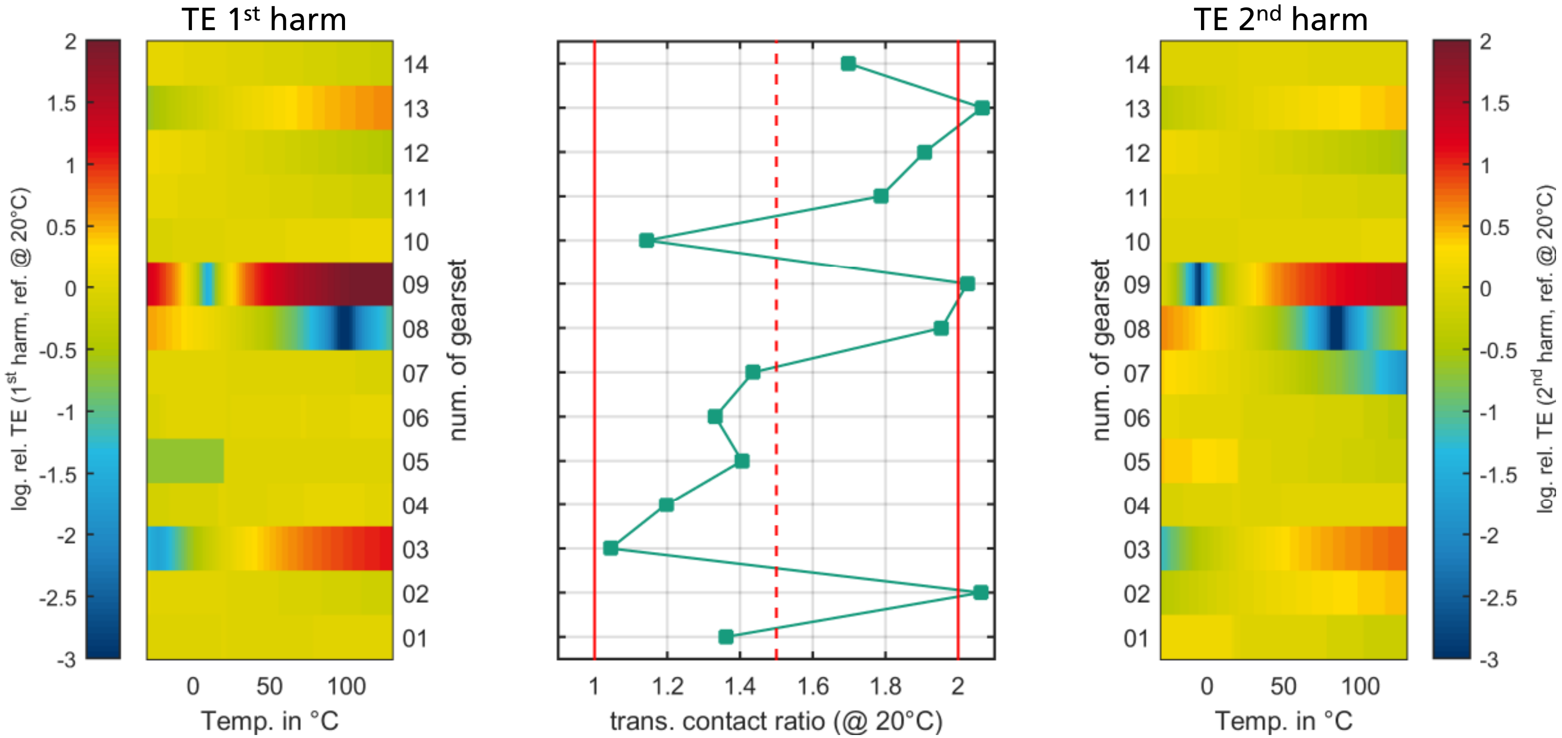
Thermal induced geometry change

Simulation results.

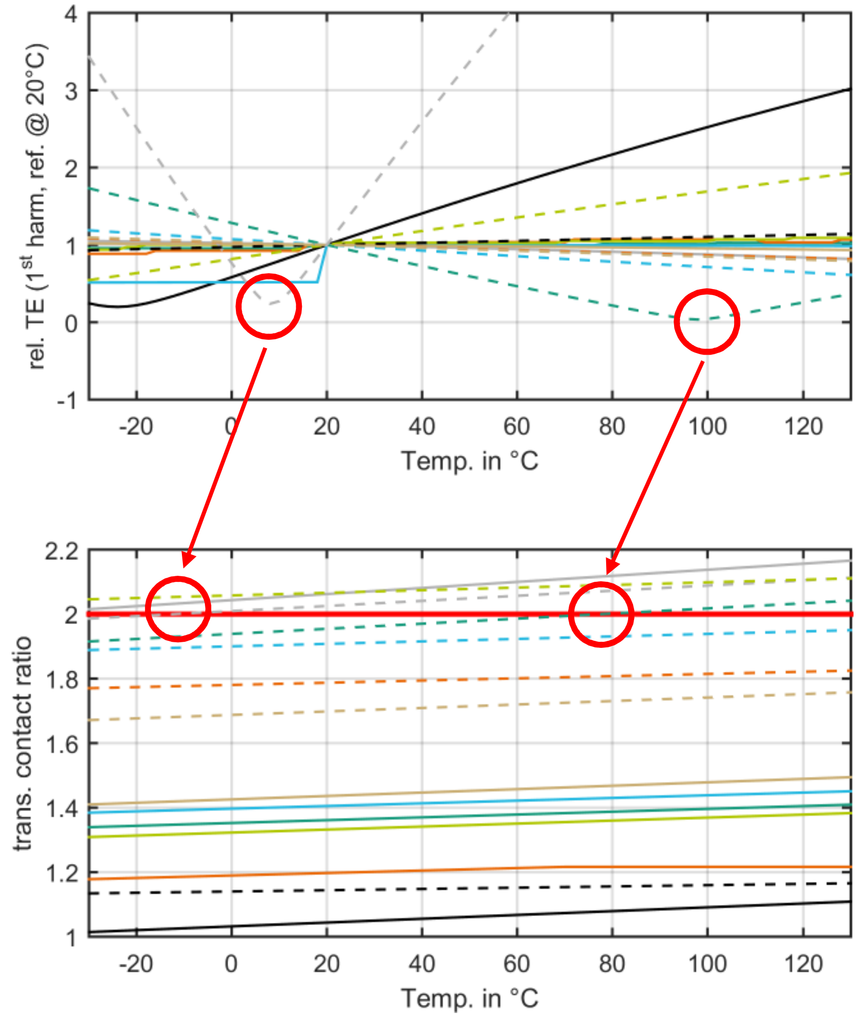
- correlation between transverse contact ratio and thermal variation in TE harmonics
- gear sets witch transverse contact ratios nearly to an integer value → significant sensitivity to thermal changes in gear geometry

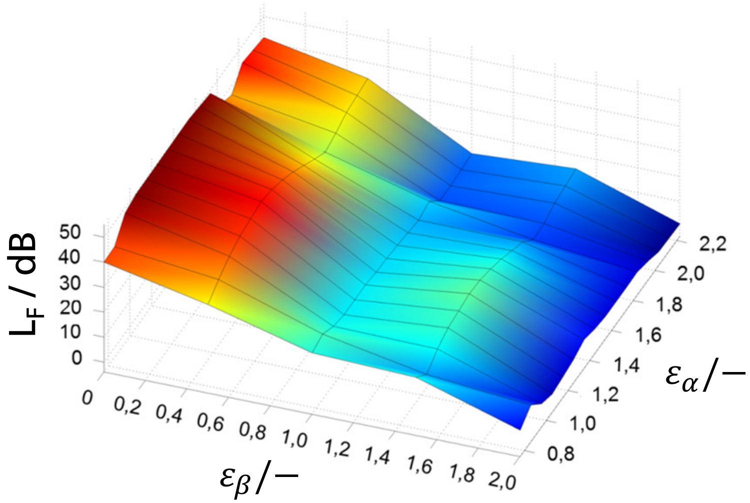


Thermal induced geometry change

Simulation results.

- correlation of simulation results with well known excitation mapping
- pass of $\varepsilon_\alpha = 2$ (or 1)
  → minimum in TE 1st harmonic
- slight differences between temperatures at minimum in TE and theoretical transverse contact ratio
  → backlash as probable reason





Conclusion and perspective

Conclusion

- thermal induced geometry changes of gear sets → slight different gear mesh ratios → variation of excitation behaviour
- consideration of thermal elongations maybe necessary (depending on gear pair parameters)
- high sensitivity near $\varepsilon_\alpha = 2 \text{ (or } 1)$ (minima and maxima by passing integer values of transverse contact ratio)
- correlation of simulation results with excitation mapping
- ROMAX batch mode → capability of "free" variation calculations using third party applications (e.g. MATLAB)

Perspective

- comparison with measurements
- consideration of thermal induced misalignments
  - e.g. shaft tilts due to thermal housing deformations
- generation of larger data basis for statistical analyses

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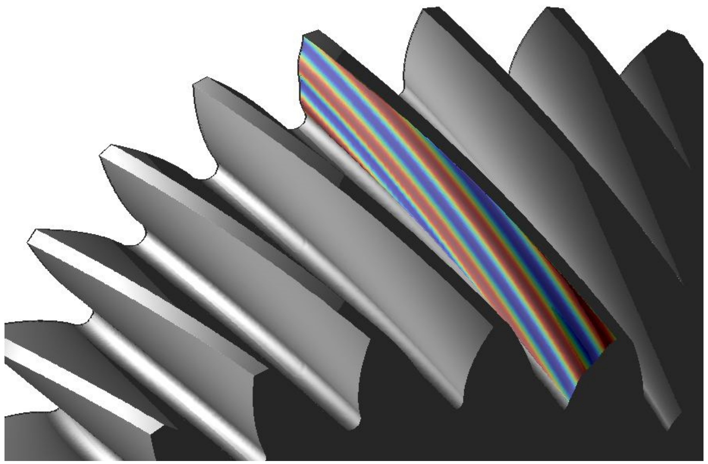
Thank you very much for your kind interest.



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Thermal induced geometry change

Calculation and Modelling.

- overview of 14 different gear sets

gear set	m_n/mm	b/mm	α_n/deg	β/deg	a/mm	$\varepsilon_\alpha/-$	$\varepsilon_\beta/-$
1	3	30	20	0	120	1.361	0
2	4	60	20	8	340	1.619	0.332
3	4	30	25	15	240	1.196	0.618
4	4	60	25	0	160	1.212	0
5	6	50	18	20	240	1.405	0.907
6	8	90	20	0	360	1.332	0
7	5	90	20	20	232	1.436	1.96
8	6	75	15	5	353	1.954	0.347
9	6	75	15	5	353	2.018	0.347
10	3	20	23	30	77	1.144	0.991
11	2	20	18	28	81	1.787	1.382
12	2	16	16	31	75	1.908	1.350
13	2.5	17	16	30	79	2.066	1.430
14	2.15	25	20	27	135	1.698	1.794

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