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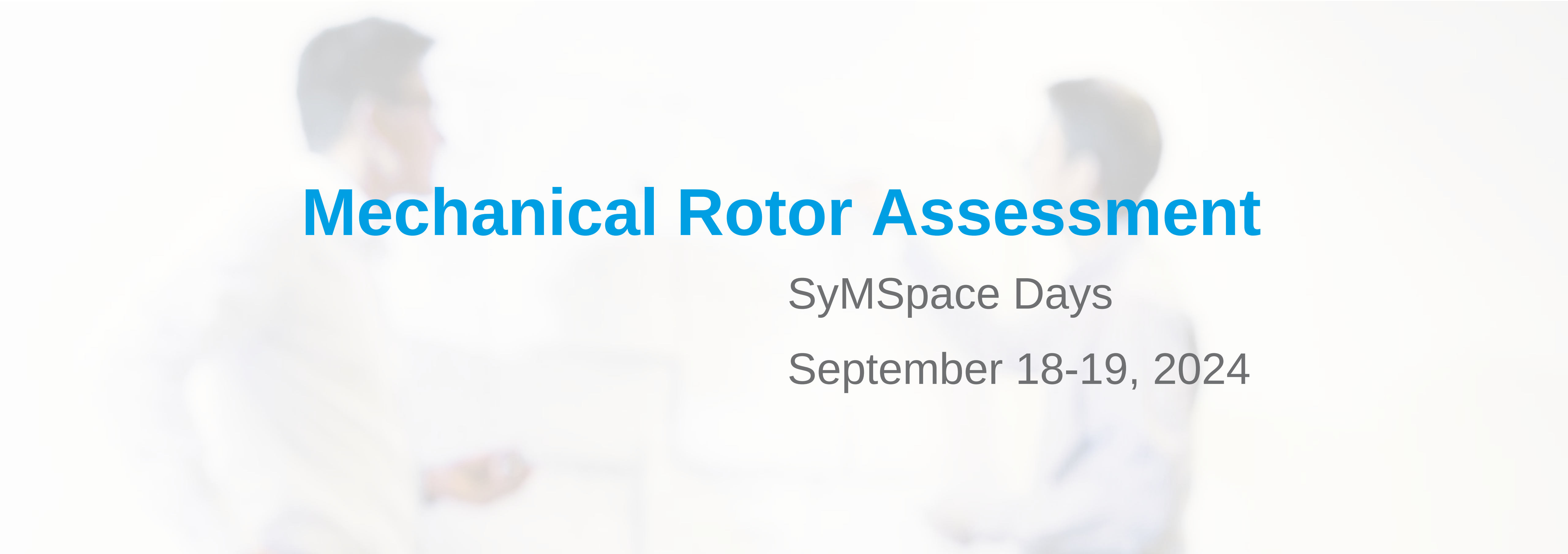


Mechanical Rotor Assessment

SyMSpace Days

September 18-19, 2024

Agenda

1. RotorStressCalc Component
2. RotorSimulation2D Component
3. Application Example

1

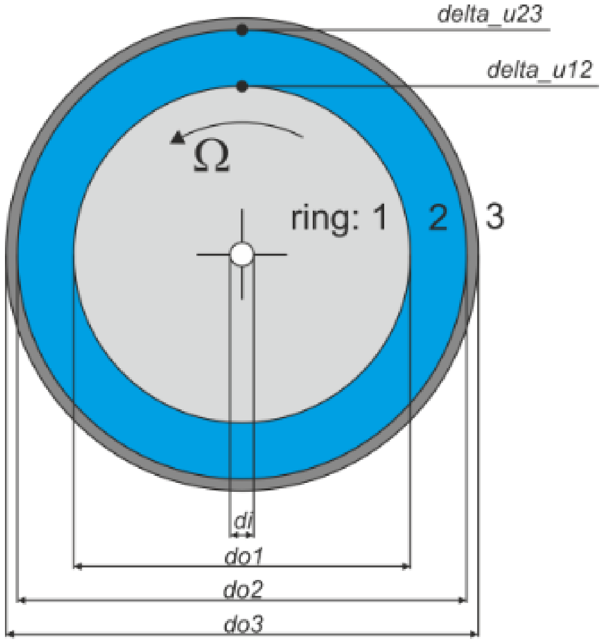
RotorStressCalc

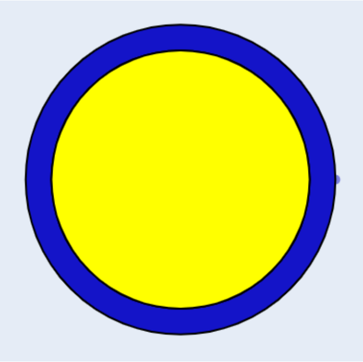
KnowledgeEngines.Mechanics.RotorStressCalc

RotorStressCalc

Base Model

- Analytically calculates the stresses in cylinders/rings due to centrifugal forces and shrink fits.
    - Please refer to the component help for a description of the component!





2

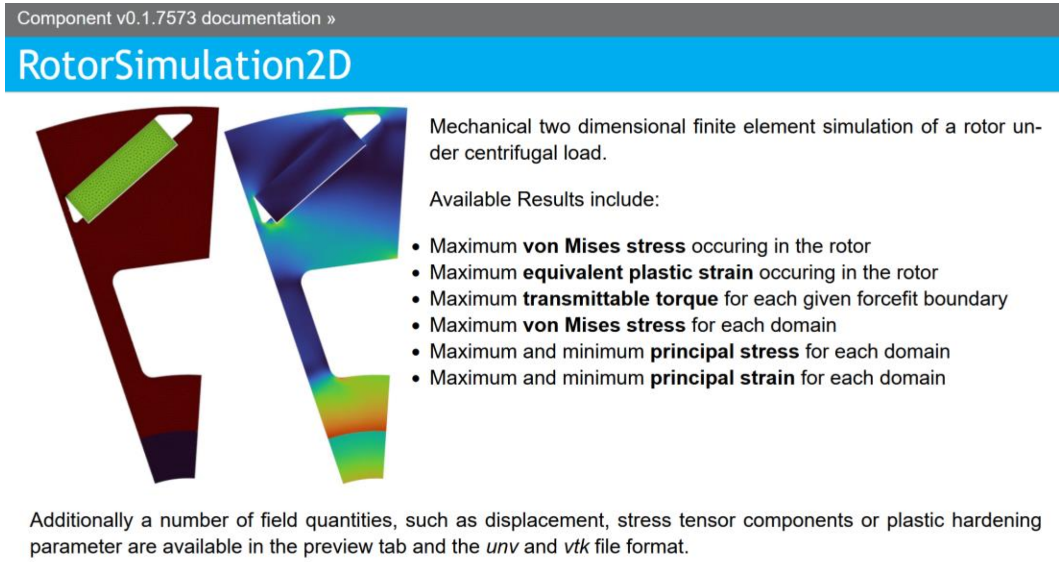
RotorSimulation2D

Simulation.Motor.Mechanical.RotorSimulation2D

Mechanical 2D Rotor Simulation

Simulation.Motor.Mechanical.RotorSimulation2D

- Simulates the mechanical stresses of a rotor due to centrifugal load and/or force-fits.
- 2D finite element simulation in HOTINT
- Boundary conditions
    - Welded
    - Contact
    - Force Fit
- Material model
    - plane stress / plane strain
    - thermal expansion
    - elasto-plastic with multi-yield plasticity



Component v0.1.7573 documentation »

RotorSimulation2D

Mechanical two dimensional finite element simulation of a rotor under centrifugal load.

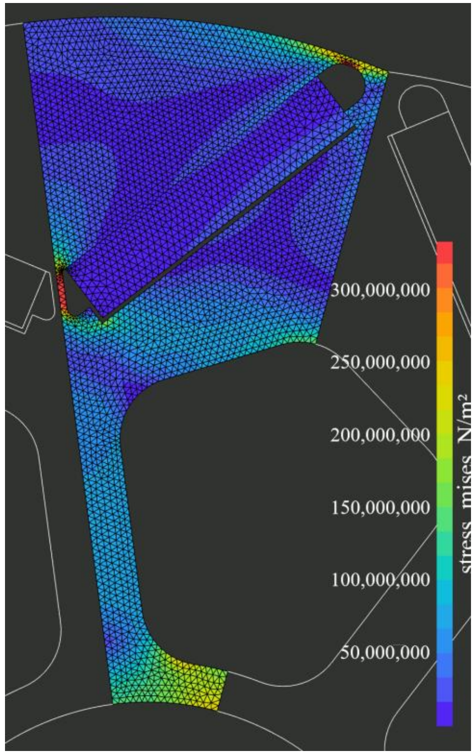
Available Results include:

- Maximum **von Mises stress** occuring in the rotor
- Maximum **equivalent plastic strain** occuring in the rotor
- Maximum **transmittable torque** for each given forcefit boundary
- Maximum **von Mises stress** for each domain
- Maximum and minimum **principal stress** for each domain
- Maximum and minimum **principal strain** for each domain

Additionally a number of field quantities, such as displacement, stress tensor components or plastic hardening parameter are available in the preview tab and the *unv* and *vtk* file format.

Mechanical 2D Rotor Simulation

- Simulation results
  - maximum occurring von Mises stresses and principal stresses / strains
  - maximum equivalent plastic strain
  - maximum transmissible torque of the force fit
  - vtk-file with displacement, strains, stresses …
  - Postprocessing components based on vtk-file are available.



Mechanical 2D Rotor Simulation

- New version replaces both RotorSimulation2D_PlaneStress and RotorSimulation2D_PlaneStrain
  - If the material is **laminated** (it has the parameter *tlam* defined) then the **plane stress** model is used as it is more accurate for thin structures.
  - **Otherwise,** the **plane strain** model is used.
  - Plasticity is implemented for both plane strain and plane stress
- Subsequent simulations are possible
  - Simulation without centrifugal load
    - Stresses and strains due to force fit. This is only useful in case of a force fit.
  - Simulation with centrifugal load
  - Simulation without centrifugal load after centrifugal loading.
    - Permanent deformation caused by the load. This is only useful in case of elasto-plastic material.
- Component was validated against rotor simulations in Abaqus and benchmark problems from literature. The validation is documented in the component help.

Implementation Status

- Technical Implementation: Done

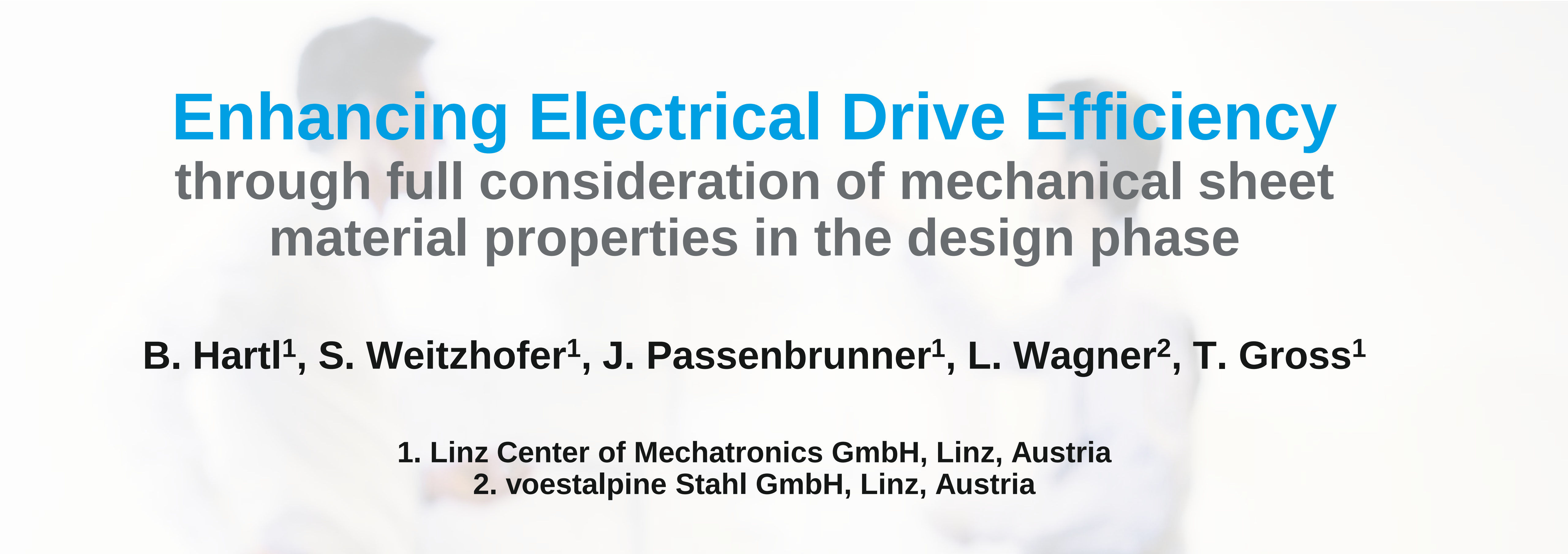
- Usability: Work in Progress
  - SyMSpace-Web
  - Reduce number of settings
  - Improve default parameter values

3

Application Example

Conference Presentation at IESSS 2024

Barbara Hartl, Research Engineer, Phone: +43 732 2468 6108, barbara.hartl@lcm.at, https://www.lcm.at



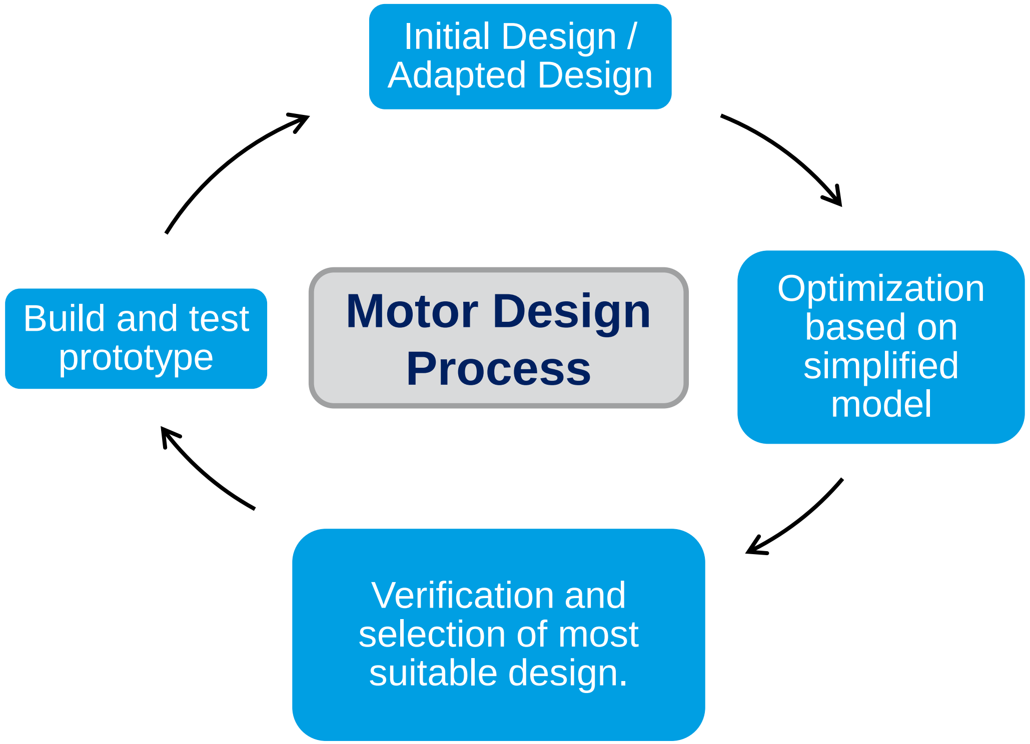
Enhancing Electrical Drive Efficiency

through full consideration of mechanical sheet material properties in the design phase

B. Hartl[1], S. Weitzhofer[1], J. Passenbrunner[1], L. Wagner[2], T. Gross[1]

1. Linz Center of Mechatronics GmbH, Linz, Austria
2. voestalpine Stahl GmbH, Linz, Austria

Designing an electric motor



Initial Design / Adapted Design

Optimization based on simplified model

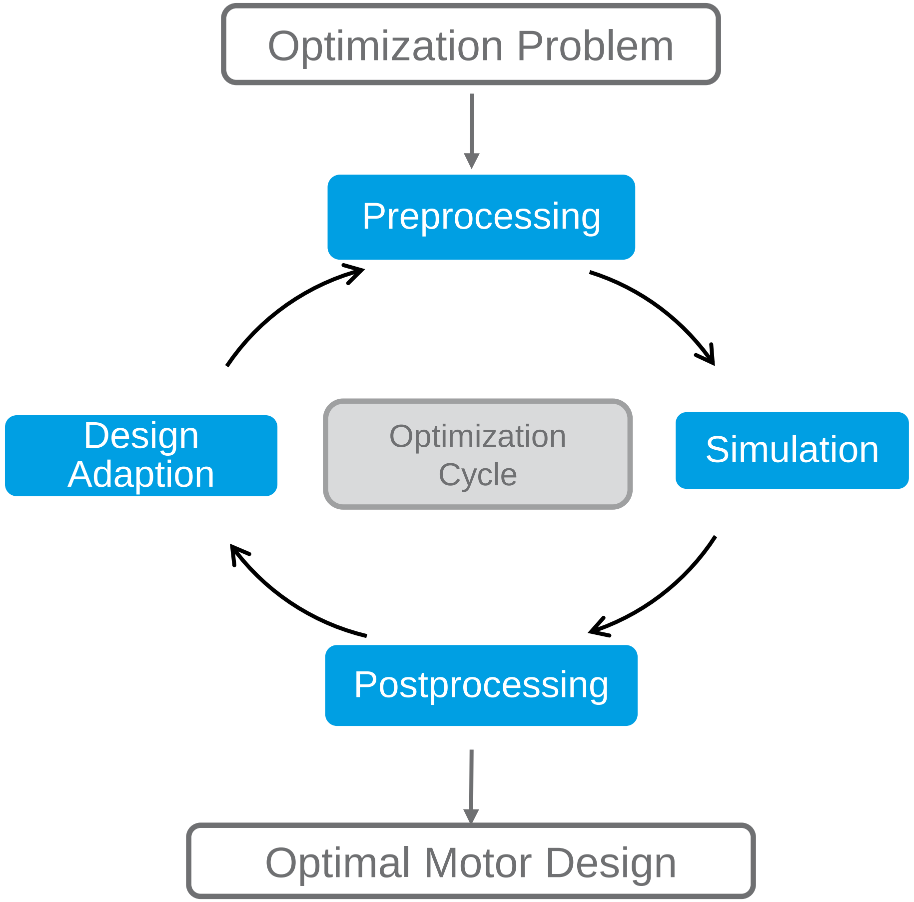
Verification and selection of most suitable design.

Build and test prototype

Motor Design Process

- To meet increasing demands in electric motors such as power, installation size, efficiency, temperature constraints, the designs **push the limits** of what is technically feasible.
- Simulation driven design engineering to:
  - improve motor properties
  - reduce development effort and time

Optimization Cycle

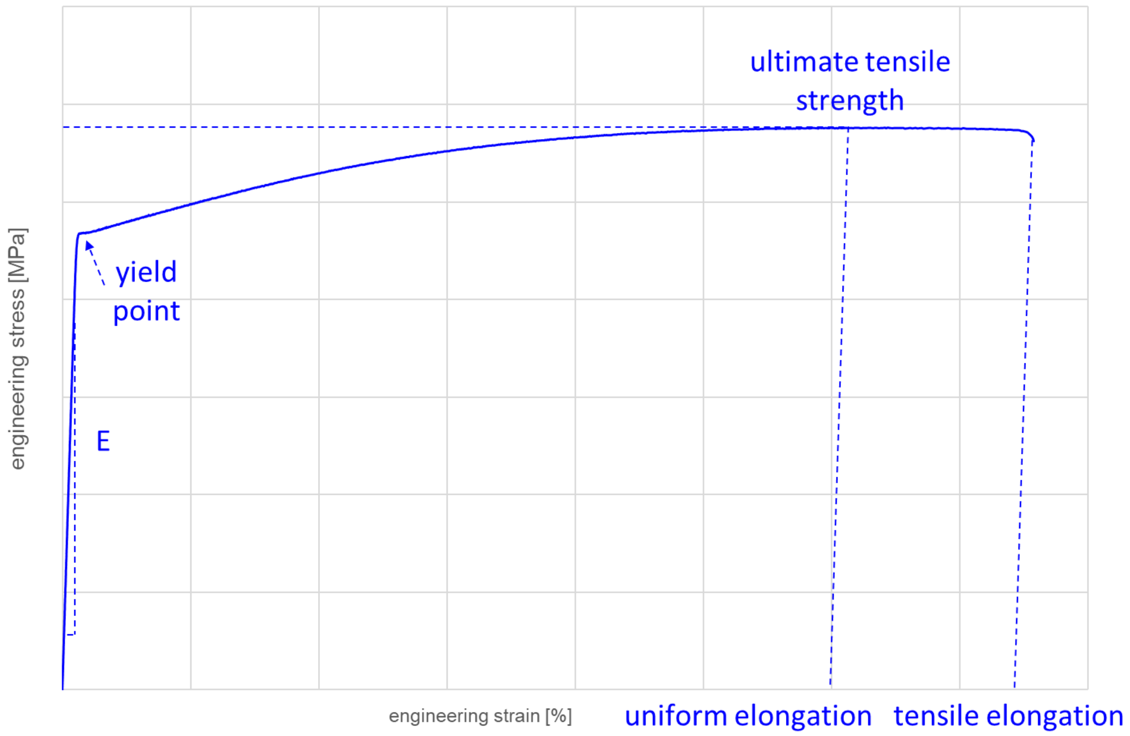


- The simulation model must include all relevant physical effects:
  - Electromagnetic simulation
  - Thermal simulation
  - Mechanical simulation
- The simulation model for the optimization must be **computationally manageable** and as **accurate** as possible
  - Inaccurate models lead to designs which may be unfeasible or not optimal
- In this presentation we will focus on the **mechanical simulation**, specifically on the influence of the mechanical properties of the electrical steel sheet

Mechanical properties of electrical steel sheets

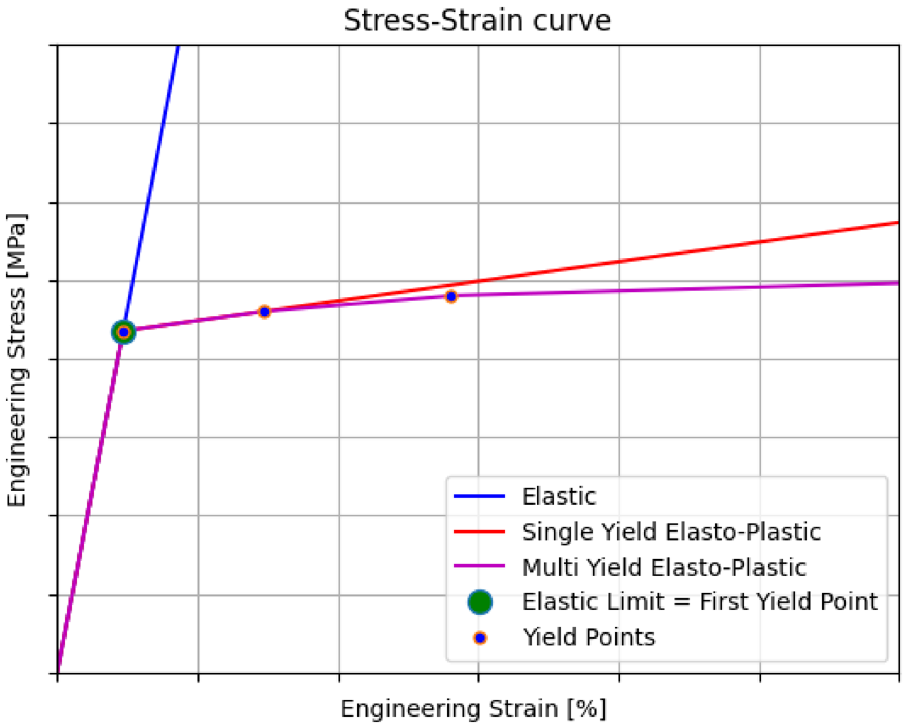
Mechanical characteristics
found in electrical sheets

- Elasticity
  - anisotropic
  - temperature dependent
- Plasticity
  - anisotropic
  - temperature dependent
  - strain rate dependent
- Magnetic properties coupled to mechanical stresses
- Trade-off between mechanical and magnetic properties



Insertion: Modeling plasticity

- Material models in the RotorStressCalc component
  - elastic material
  - single-yield elasto-plastic material
  - multi-yield elasto-plastic material



What is the influence of the electrical sheet’s material model?

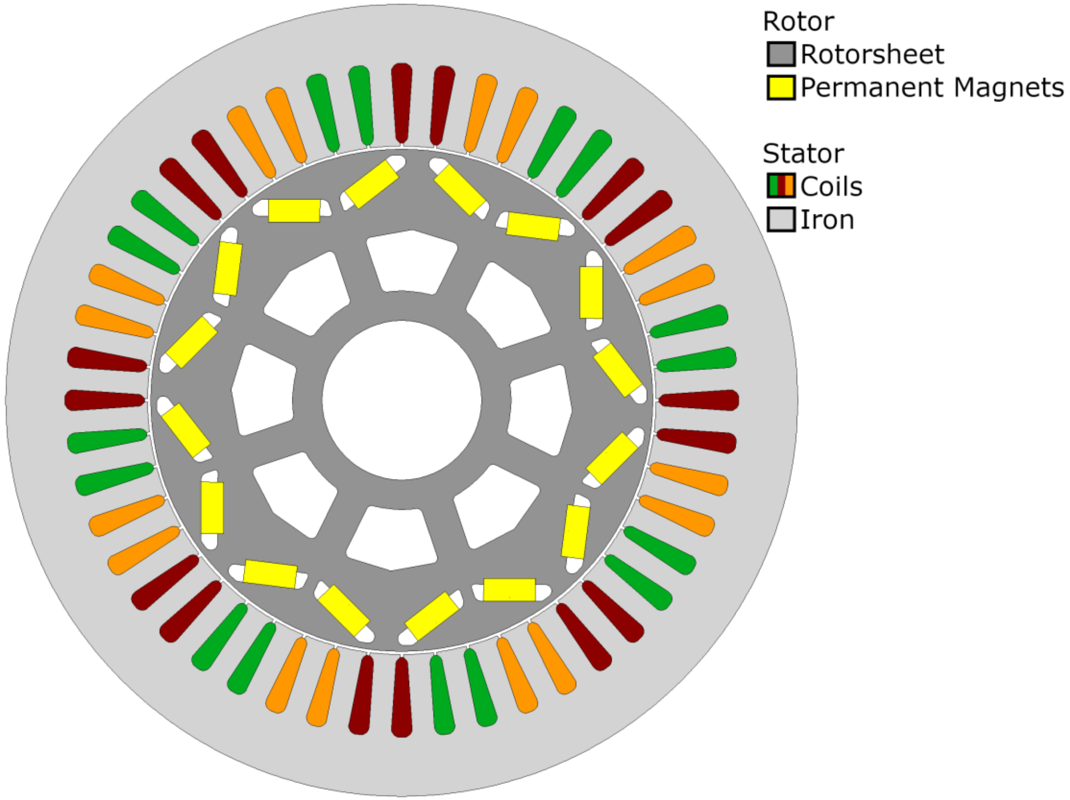
Topic of this talk

- The classic optimization approach is to assign **elastic material behavior** and reject a design, if the stress occurring under load exceeds a defined limit such as the **yield strength**.
- Public data sheets of electrical sheets contain very few mechanical properties.
- Study to investigate how accounting for **elasto-plastic behavior** in simulations impacts electrical drive optimization.
- **Hypothesis**: allowing for small plastic deformation in the design loop will lead to enhanced drive design
- In this talk we compare the results of a drive optimization using:
  - an elastic material model
  - an elasto-plastic material model

Motor Design

- Motor design similar to Toyota Prius 2010
  - v-shape rotor design
  - broadly discussed in literature [1]

- Motor minimal requirements
  - Nominal Torque: 70 Nm at 2770 rpm
  - Peak Torque: 200 Nm at 2770 rpm
  - Maximum speed: 14 550 rpm
  - Non-operational speed: 17 460 rpm
  - Minimum DC link voltage: 650 V

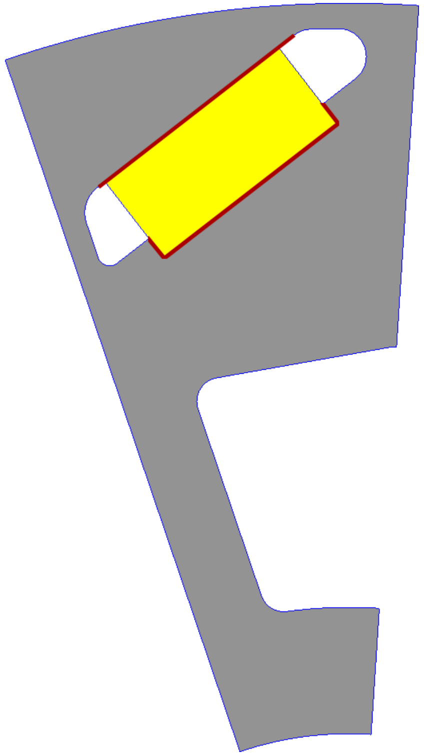


Motor with permanent magnets forming Vs

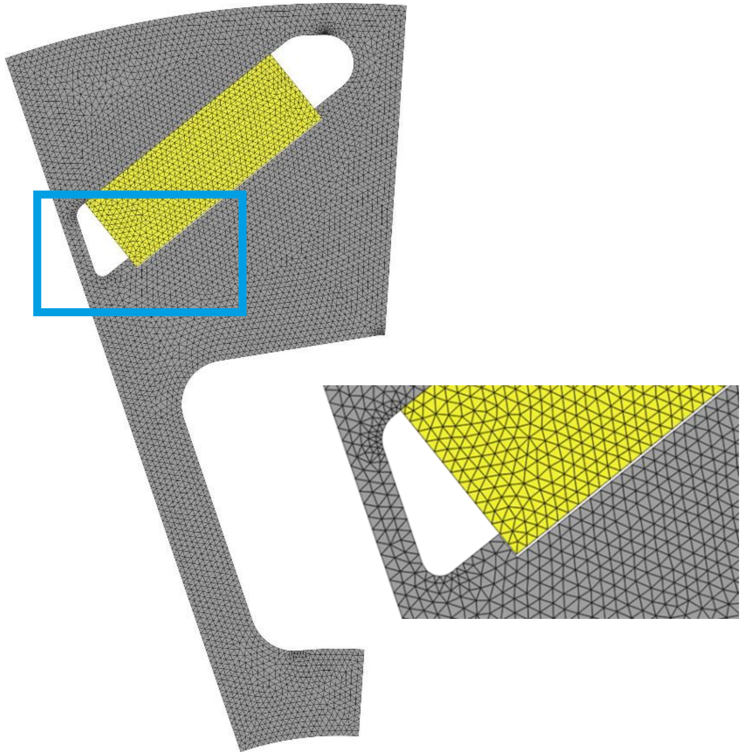
[1] Burress; Campbell; Coomer; Ayers; Wereszczak; Cunningham; Marlino; Seiber; Lin; **Evaluation of the 2010 Toyota Prius Hybrid Synergy Drive System**. United States. 2011. https://doi.org/10.2172/1007833

Mechanical Simulation

- Finite element simulation
- 2D geometry
- Symmetry is utilized
- Mesh with linear triangular elements
- Material models
  - plane stress for rotor sheets
  - plane strain for magnets
- Contact between rotor core and magnets

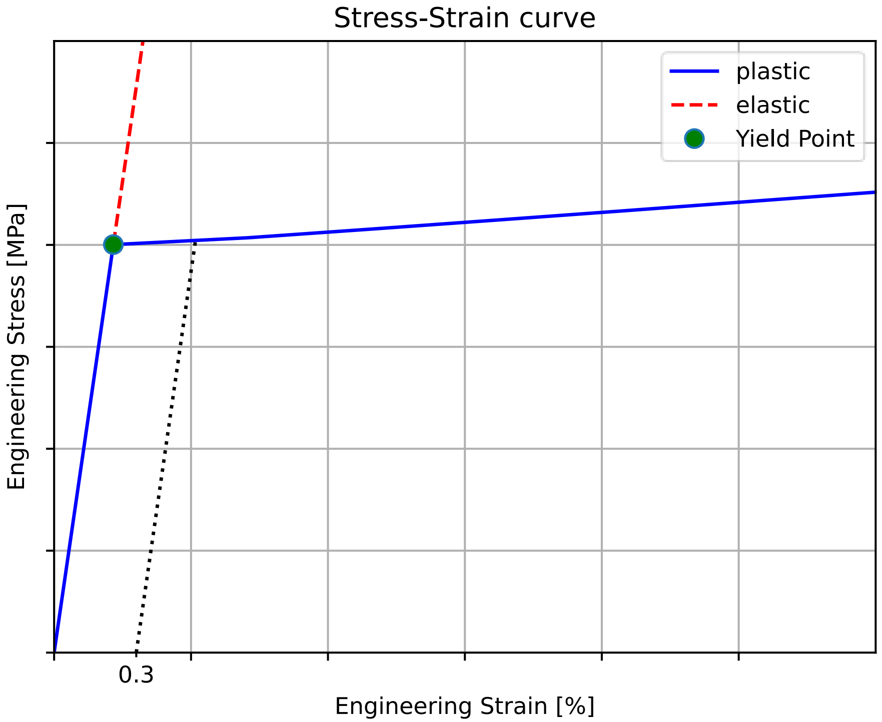


contact boundary condition



FE mesh

Material model



- In the drive optimization we compare two material models, namely
  - linear elastic material model
    - von Mises stress must be less than yield stress
  - elasto-plastic model
    - equivalent plastic strain must be less than 0.3%

3

Optimization Results

Motor design optimization

- Multi objective optimization
  - minimize stator terminal current
  - minimize motor mass
  - minimize material costs
  - minimize rotor torque ripple
  - minimize losses
  - minimize coil temperature
  - minimize plastic strain

- Pareto optimal motor designs
  - a motor design is Pareto optimal if there is no other design which is better in all objectives.

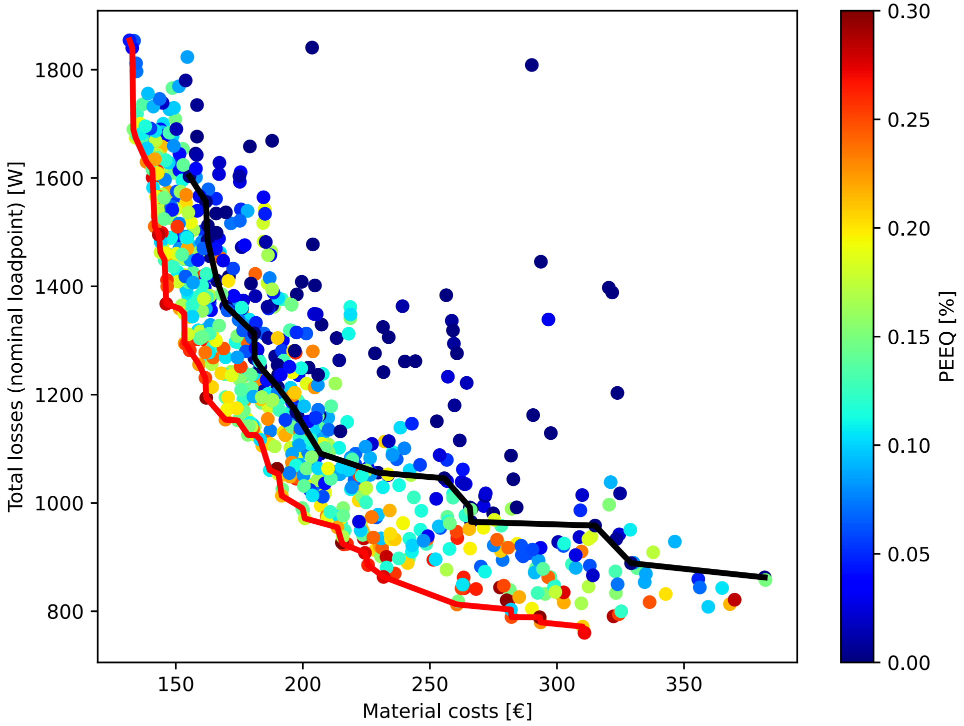
- Maximum equivalent plastic strain (PEEQ) at non-operational speed is constrained to a maximum of 0.3%

- Maximum temperature in coil is constrained to 120 °C above stator surface temperature

Simulation Results

Losses and Costs

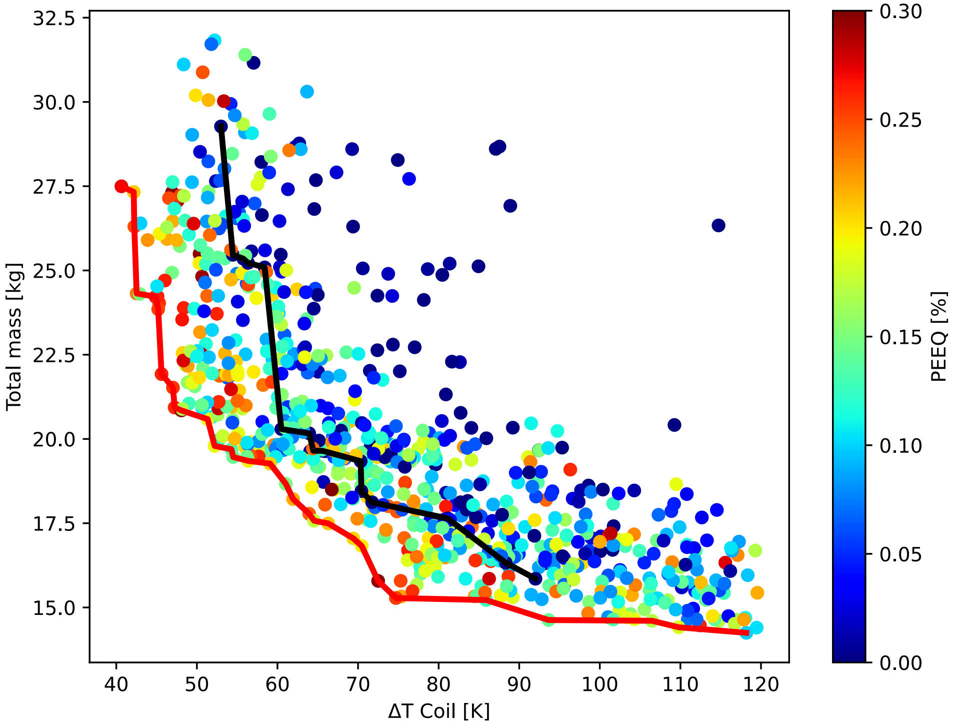
- In total 7 objectives
- Plot compares material costs and losses
- Color indicates the maximum equivalent plastic strain of the rotor under centrifugal load at non-operational speed.
- The red line shows the pareto front for elasto-plastic designs.
- The black line shows the pareto front for the elastic designs.
- Allowing for small plastic strains decreases costs and increases efficiency.



Simulation Results

Mass and Temperature

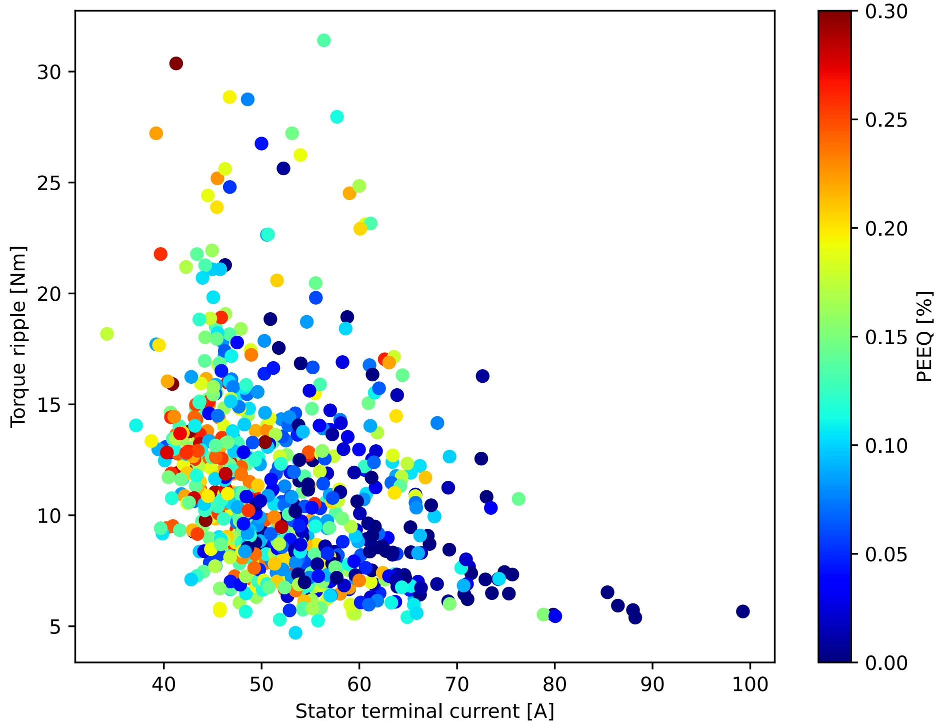
- Plot compares motor mass and temperature.
- Color indicates the maximum equivalent plastic strain of the rotor under centrifugal load at non-operational speed.
- The red line shows the pareto front for elasto-plastic designs.
- The black line shows the pareto front for the elastic designs.
- The black line shows the pareto frontier
- Allowing for plasticity decreases weight and temperature.



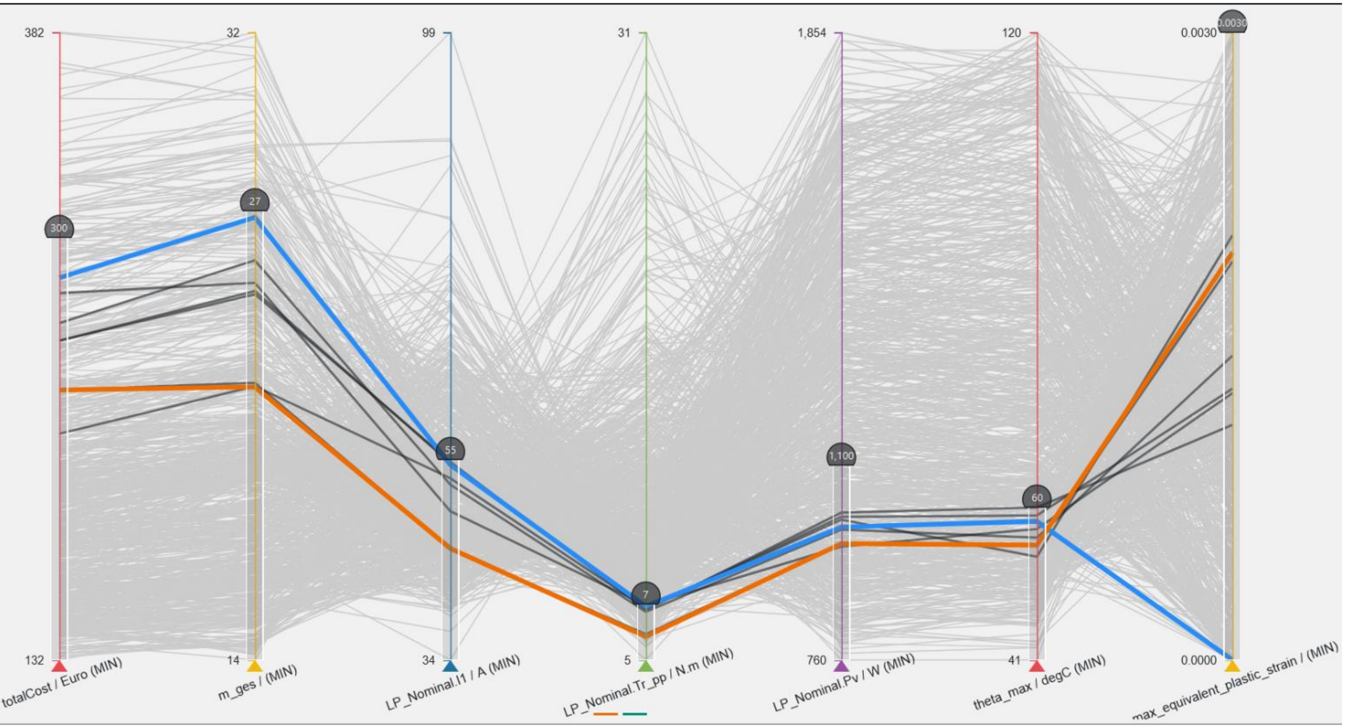
Simulation Results

Torque Ripple and Terminal Current

- Plot compares torque ripple and stator terminal current
- A high torque ripple induces vibrations
- Higher stator terminal currents require better and more expensive power electronics
- Color indicates the maximum equivalent plastic strain of the rotor under centrifugal load at non-operational speed.
- Plasticity does not seem to improve torque ripple, but it does reduce the stator terminal current and thus the costs for power electronics. (Better power factor)

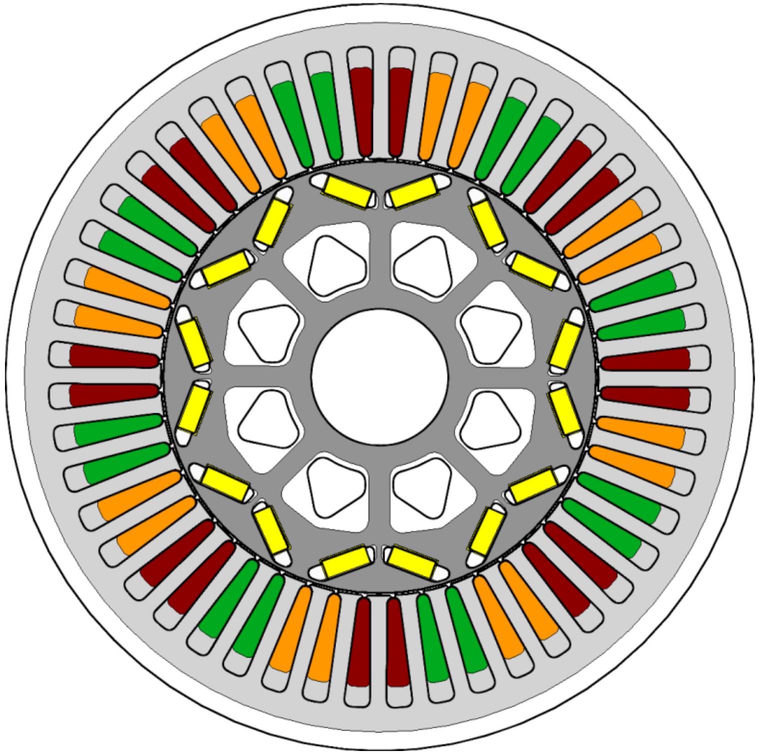


Comparison of an elastic and a plastic design



- Selected a pareto optimal design which does not require considering plasticity (blue)
  - Torque ripple should be below 10% of nominal torque
  - Temperature of coil should be not more than 60°C above stator outside temperature
- Compared to a design which allows plasticity at non-operational speed (orange)
  - Selected a design which is better in each other criteria

Comparison of an elastic and a plastic design



Comparison of the motor design with plastic strain at non-operational speed (colored)
and the motor design within the elastic limits at non-operational speed (contour)

The motor design allowing for plasticity has

- 16% lower stator terminal current
- 18% less weight
- 16% cheaper material cost
- 18% less torque ripple
- 3% fewer losses
- 5% less temperature difference between coil and stator outside
- 5% smaller diameter

compared to the motor design not allowing for plastic strains at non-operational speed.

Resume and Outlook

- The optimization of permanent magnet synchronous motors (PMSM) lead to rotor designs with **maximum mechanical loading**.
- Optimization considering elasto-plastic material behavior leads to **improved motor designs.**
- Considering plasticity in the optimization cycle reduces development efforts and thus **development time** and **costs**.

- Outlook: Improvements of mechanical simulation model (already implemented or work in progress)
  - Considering thermal expansion of material
  - Temperature dependent material parameters
  - Elastic and plastic anisotropy

Stay
Tuned

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