Advancing Structural Optimization of an Electric Motor Rotor through Mesh Morphing Techniques

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Overview

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- Background
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  - Biological Growth Method
  - Automatic Surface Sculpting
- Numerical model
- Parameter Based Optimization
- Parameter-Less Optimization
- Optimization Results
- Conclusions

Introduction

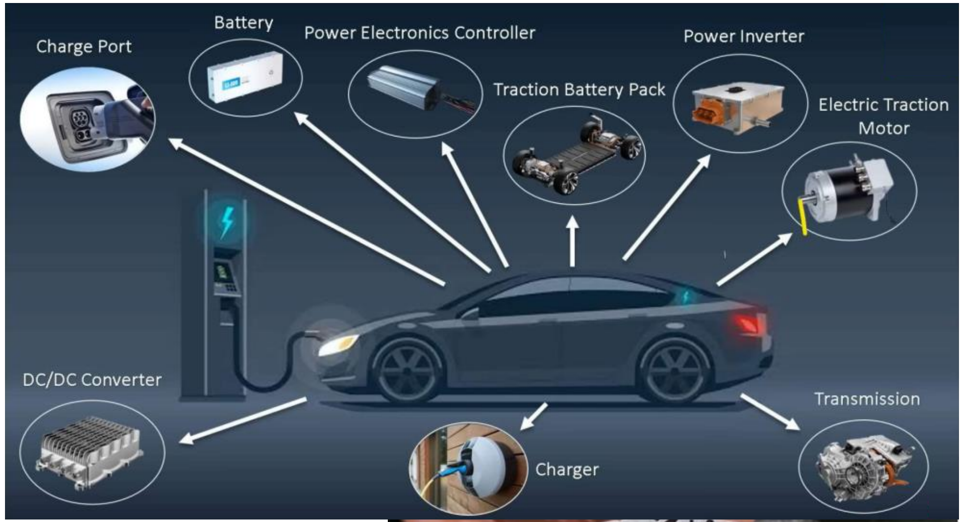
- Vehicle equipped with **electric motor** (EM) are increasing their diffusion both in Europe and other countries
- The main **advantages** of this kind of motors are:
  - high **torque and power to weight ratio**;
  - high **silence**;
  - lower **maintenance costs**;
  - lower **operating costs**;
  - lower **environmental impact**.
- The **importance** of this kind of motors is clear, and so the importance of designing components in order to **optimize** material, costs, weight, efficiency.

Introduction

- In this work an overview of how to advance **structural optimization** of EM thanks to Radial Basis Functions (RBF) based **mesh morphing** is given
- Two **approaches** are presented and used to optimize a Finite Element Method (FEM) model of a generic EM: **Parameter Based Optimization** and **Parameter-Less Optimization**
- In Parameter Based Optimization, structural **mesh is made parametric** by means of geometrical parameters. The parametric FEM model is used to evaluate results to feed a **meta-model based optimization**
- In Parameter-Less Optimization, RBF based **mesh morphing** is coupled with Biological Growth Method (BGM) to drive optimization by **sculpting** surfaces according to **surface stress distribution**.

Electric Vehicle Design

- **Electric Vehicle** (EV) design requires facing a high number of **design challenges** regarding **EV characteristics**
- Furthermore, each design challenge involves **more than one physics**
- Considering, for example, only the EM **rotor** requires **electric**, **electromagnetic**, **thermal**, **structural**, **durability** and **comfort analyses**



Electric Vehicle Design

Problem Definition
- Motor Geometry
- Drive Parameters

Electric Circuit
- Windig Current

Electromagnetic Solution
- Flux density, power
- Torque, losses, ecc.

Forces
- Stator toot forces (radial and tangential)

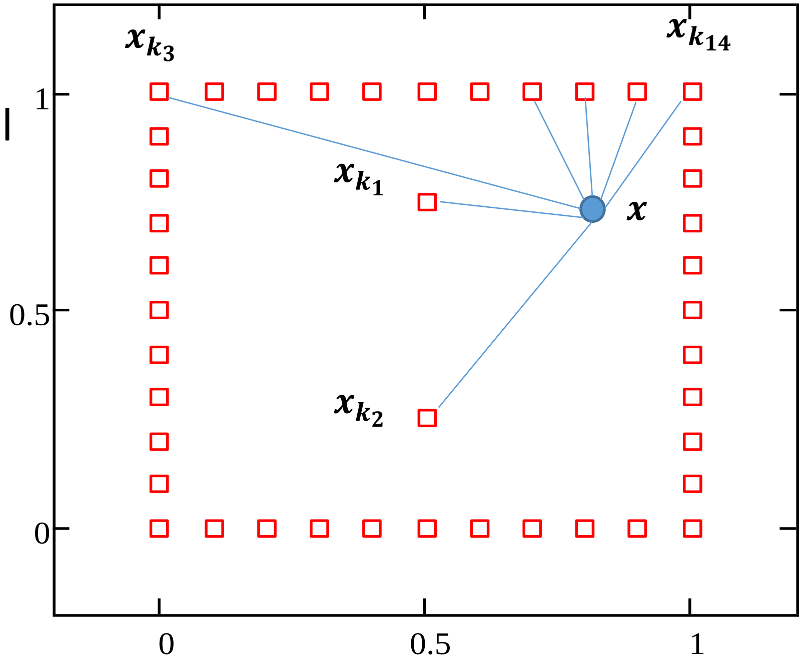
Structural Analysis
- Modal study, harmonic study,
- Stress evaluation, durability, ecc.

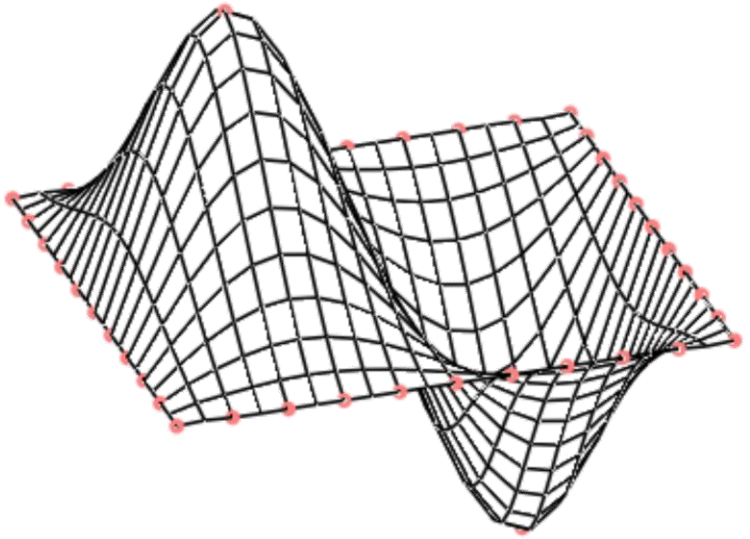
- In the present work, the attention will be focused on the Structural Analysis
- The presented approach (RBF based mesh morphing) can be used to update numerical models used in different physics simulations, being a meshless method

Background on RBF

- RBFs are a mathematical tool capable to **interpolate** in a generic point in the space a function **known** in a discrete set of points (**source points**).
- The interpolating function is composed by a **radial basis** and by a **polynomial**:

$$s(\mathbf{x}) = \sum_{i=1}^{N} \overbrace{\gamma_i \varphi\left(\underbrace{\left\|\mathbf{x}-\mathbf{x}_{k_i}\right\|}\right)}^{\text{radial basis}} + \overbrace{h(\mathbf{x})}^{\text{polynomial}}$$





Background on RBF

- If evaluated on the source points, the interpolating function gives exactly the input values:

$$\begin{aligned} s(\boldsymbol{x}_{k_i}) &= g_i \\ h(\boldsymbol{x}_{k_i}) &= 0 \end{aligned} \qquad 1 \le i \le N$$

- The RBF problem (evaluation of coefficients γ and β) is associated to the solution of the linear system, in which **M** is the interpolation matrix, **P** is a constraint matrix, **g** is the vector of known values on the source points:

$$\begin{bmatrix} \mathbf{M} & \mathbf{P} \\ \mathbf{P}^{\mathrm{T}} & 0 \end{bmatrix} \begin{pmatrix} \boldsymbol{\gamma} \\ \boldsymbol{\beta} \end{pmatrix} = \begin{pmatrix} \boldsymbol{g} \\ 0 \end{pmatrix} \qquad M_{ij} = \varphi\left(\boldsymbol{x}_{k_i} - \boldsymbol{x}_{k_j}\right) \qquad 1 \le i, j \le N \qquad \mathbf{P} = \begin{bmatrix} 1 & x_{k_1} & y_{k_1} & z_{k_1} \\ 1 & x_{k_2} & y_{k_2} & z_{k_2} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_{k_N} & y_{k_N} & z_{k_N} \end{bmatrix}$$

Background on RBF

- Once solved the RBF problem each displacement component is interpolated:

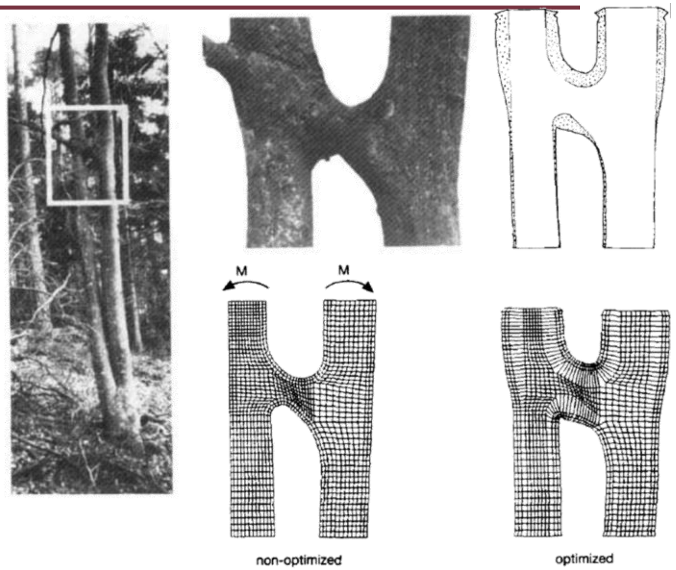
$$
\begin{cases}
s_x(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^x \varphi\left(\boldsymbol{x} - \boldsymbol{x}_{\boldsymbol{k}_i}\right) + \beta_1^x + \beta_2^x x + \beta_3^x y + \beta_4^x z \\
s_y(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^y \varphi\left(\boldsymbol{x} - \boldsymbol{x}_{\boldsymbol{k}_i}\right) + \beta_1^y + \beta_2^y x + \beta_3^y y + \beta_4^y z \\
s_z(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^z \varphi\left(\boldsymbol{x} - \boldsymbol{x}_{\boldsymbol{k}_i}\right) + \beta_1^z + \beta_2^z x + \beta_3^z y + \beta_4^z z
\end{cases}
$$

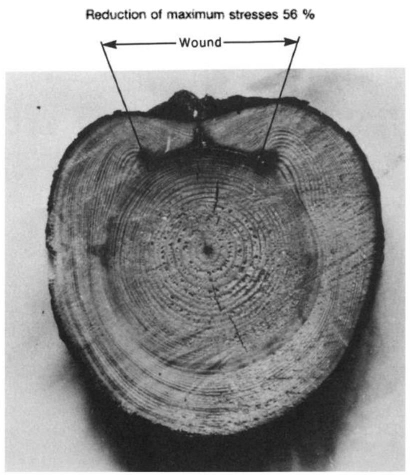
- Several different radial function (kernel) can be employed:

RBF	**φ(r)**	**RBF**	**φ(r)**
Spline type (Rn)	r^n, *n odd*	Inverse multiquadratic (IMQ)	$\frac{1}{\sqrt{1+r^2}}$
Thin plate spline	$r^n \log(r)$ *n even*	Inverse quadratic (IQ)	$\frac{1}{1+r^2}$
Multiquadratic (MQ)	$\sqrt{1+r^2}$	Gaussian (GS)	e^{-r^2}

Background on BGM

- **BGM** approach is based on the observation that **biological** structures growth is driven by **local** level of **stress**.
- Bones and trees' trunks are able to **adapt the shape** to mitigate the stress level due to external loads.
- The process is driven by stress **value at surfaces**. Material can be **added or removed** according to local values.
- Was proposed by Mattheck & Burkhardt in 1990*





Background on BGM

- The BGM idea is that surface growth can be expressed as a **linear law** with respect to a given threshold value:

$$\dot{\varepsilon} = k\left(\sigma_{Mises} - \sigma_{ref}\right)$$

- Waldman and Heller* refined this first approach proposing a **multi peak** one:

$$d_i^j = \left(\frac{\sigma_i^j - \sigma_i^{th}}{\sigma_i^{th}}\right) \cdot s \cdot c\,, \qquad \sigma_i^{th} = max(\sigma_i^j) \text{ if } \sigma_i^j > 0 \quad \text{or} \quad \sigma_i^{th} = min(\sigma_i^j) \text{ if } \sigma_i^j < 0$$

- In **ANSYS RBF Morph Structures** a different implementation is present and different **stress types** can be used to modify the surface shape:

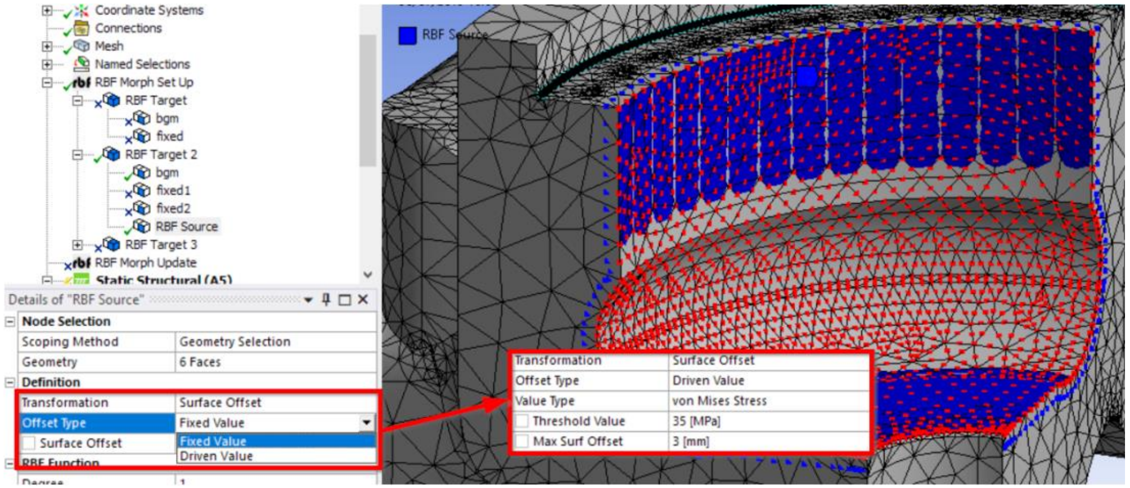
$$S_{node} = \frac{\sigma_{node} - \sigma_{th}}{\sigma_{max} - \sigma_{min}} \cdot d$$

Stress/strain type	Equation	Stress/strain type	Equation
von Mises stress	$\sigma_e = \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$	Stress intensity	$\sigma_e = max(\lvert\sigma_1 - \sigma_2\rvert, \lvert\sigma_2 - \sigma_3\rvert, \lvert\sigma_3 - \sigma_1\rvert)$
Maximum principal stress	$\sigma_e = max(\sigma_1, \sigma_2, \sigma_3)$	Maximum Shear stress	$\sigma_e = 0.5 \cdot (max(\sigma_1, \sigma_2, \sigma_3) - min(\sigma_1, \sigma_2, \sigma_3))$
Minimum principal stress	$\sigma_e = min(\sigma_1, \sigma_2, \sigma_3)$	Eqv. plastic strain	$\varepsilon_e = [2(1+\nu')]^{-1} \cdot \left(0.5\sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2}\right)$

*Waldman W., Heller M., 2015. Shape optimization of holes in loaded plates by minimization of multiple stress peaks, Defence Science and Technology Organisation Fisherman Bend, Australia, Aerospace Div, http://www.dtic.mil/docs/citations/ADA618562.

Automatic Surface Sculpting

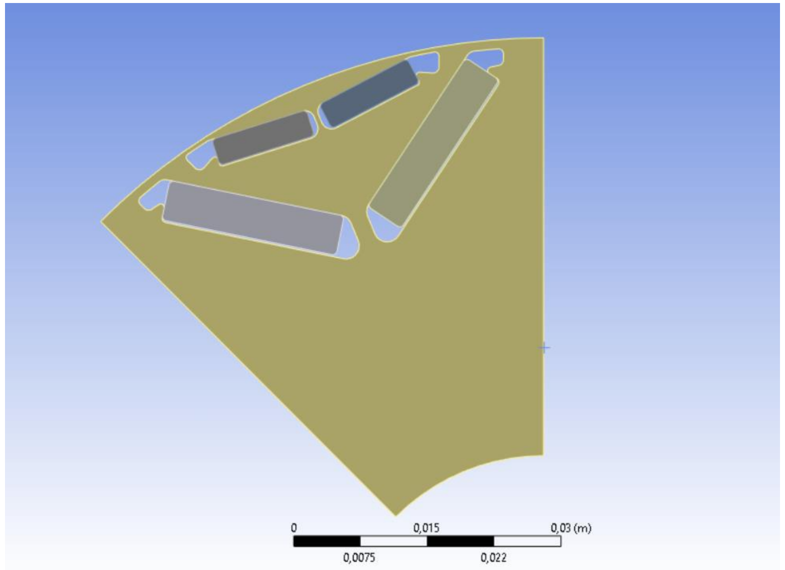
- Automatic optimization is accoplished connecting adjoint and BGM data from numerical simulation to mesh morphing tool.
- Offset Surface shape modification allow to define for each node a displacement according to the local normal direction.
- When using BGM data, the direction and amplitude of displacement is defined according to BGM stress data, considering the threshold stress value σ_{th} and the d maximum displacement.

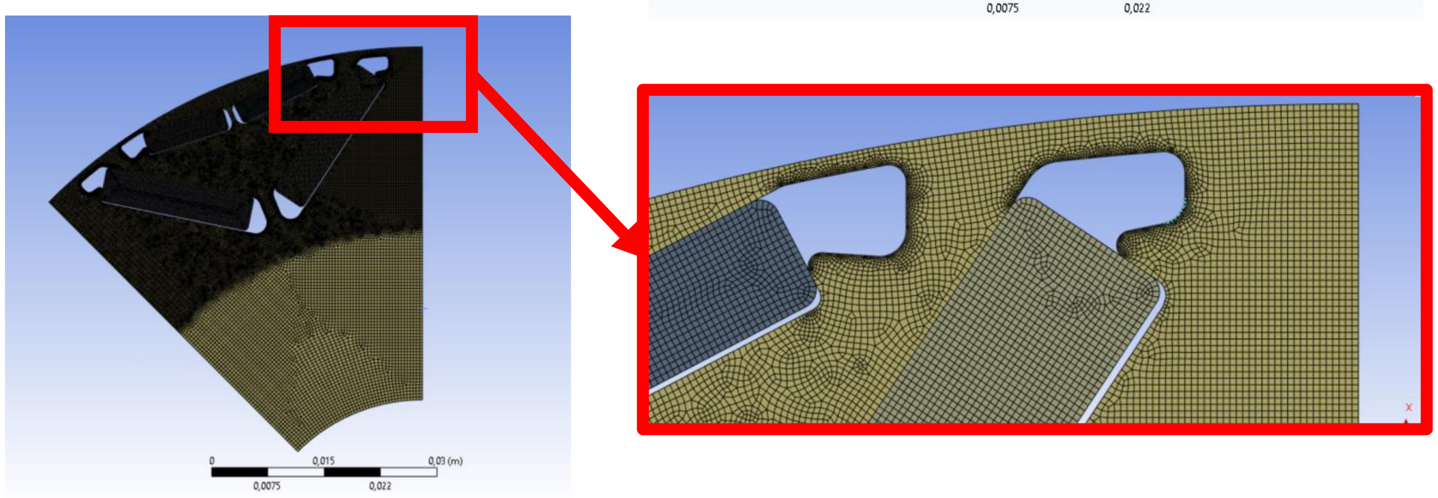


$$S_{node} = \frac{\sigma_{node} - \sigma_{th}}{\sigma_{max} - \sigma_{min}} \cdot d$$

Numerical Model

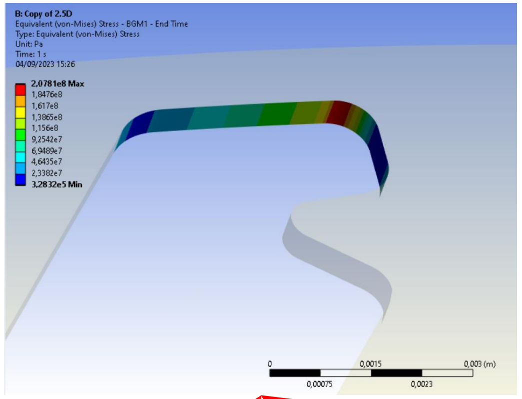
- FEM model uses axial symmetry (45° sector)
- Rotational velocity = 1885 rad/s
- Magnets contact is bonded
- Frictionless supports for axis-symmetric and planar strain
- Total nodes = 342875
- Total elements = 47756
- Mesh refinements used to augment result resolution in high stress zones (hot-spots)

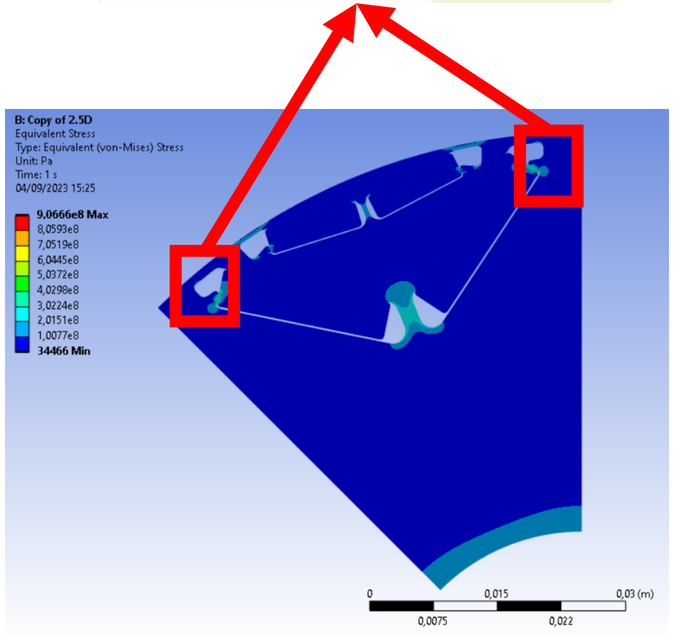




Numerical Model – Baseline results

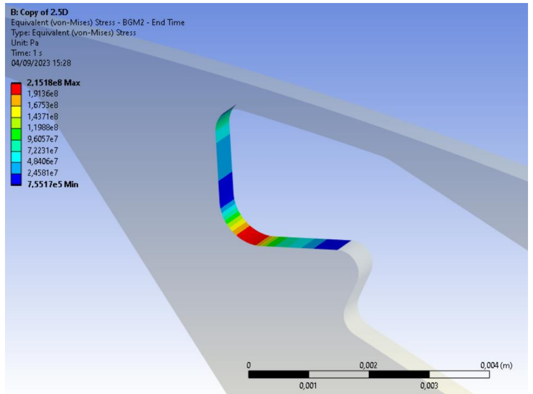
- Hot spot interested in this optimization are located at magnets housings fillets
- Hot-spot 1:
  - Maximum equivalent stress: 208 MPa

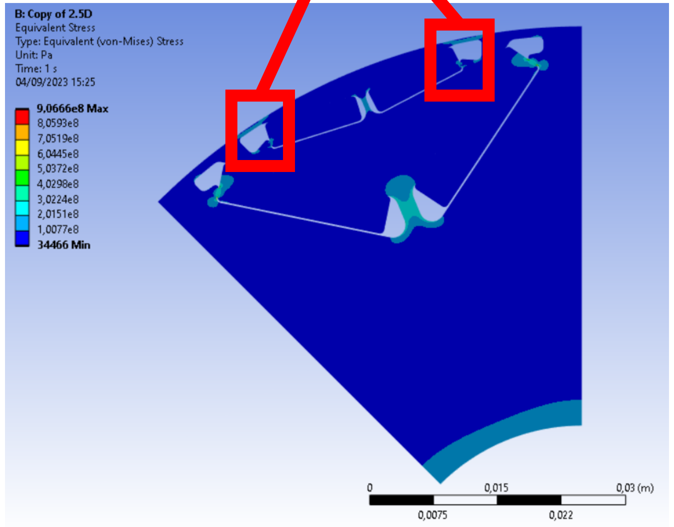




Numerical Model – Baseline results

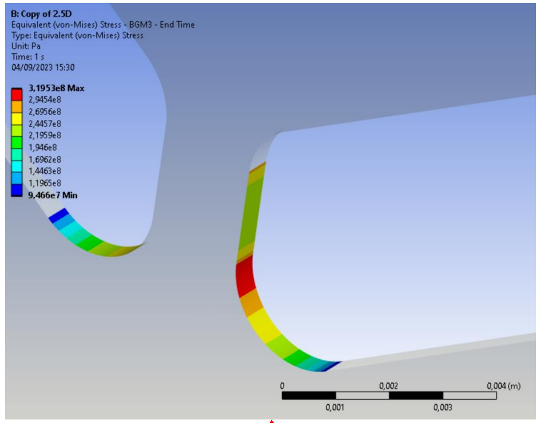
- Hot spot interested in this optimization are located at magnets housings fillets
- Hot-spot 1:
  - Maximum equivalent stress: 208 MPa
- Hot-spot 2:
  - Maximum equivalent stress: 215 MPa

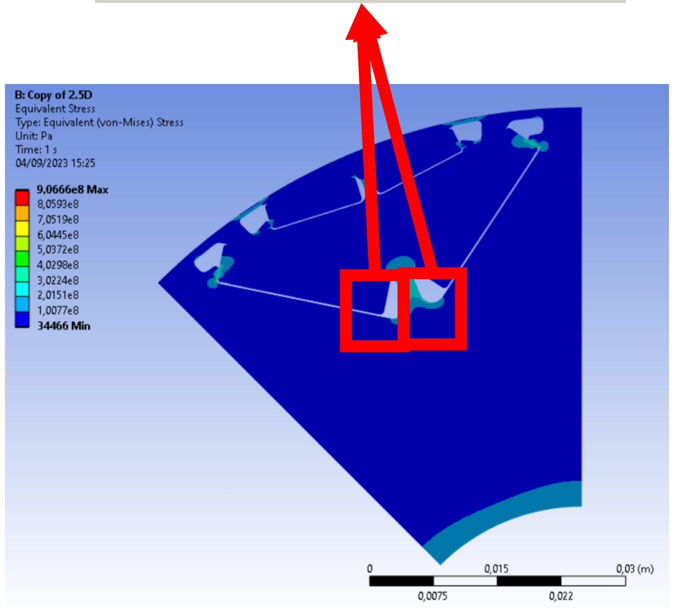




Numerical Model – Baseline results

- Hot spot interested in this optimization are located at magnets housings fillets
- Hot-spot 1:
  - Maximum equivalent stress: 208 MPa
- Hot-spot 2:
  - Maximum equivalent stress: 215 MPa
- Hot-spot 3:
  - Maximum equivalent stress 319 MPa

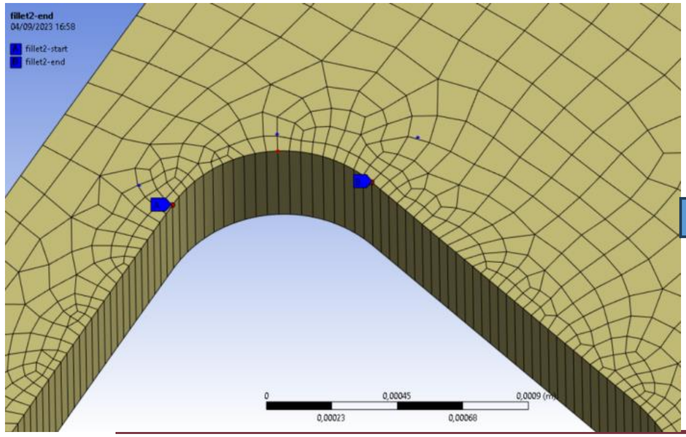




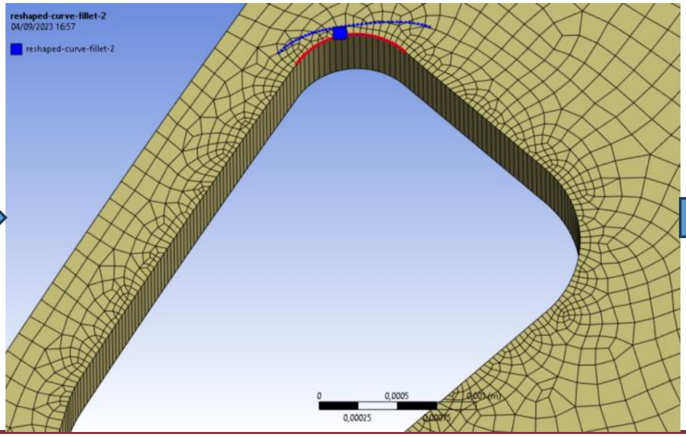
Parameter Based Optimization

- The parametric shape optimization is controlled by means of 3 parameters for each fillet profile to be optimized (total 9 parameters)
- Start point, mid point and end point displacement are used to control fillet shape
- Fillet shape is the used to modify the whole magnet housing area which is not in contact with the magnet

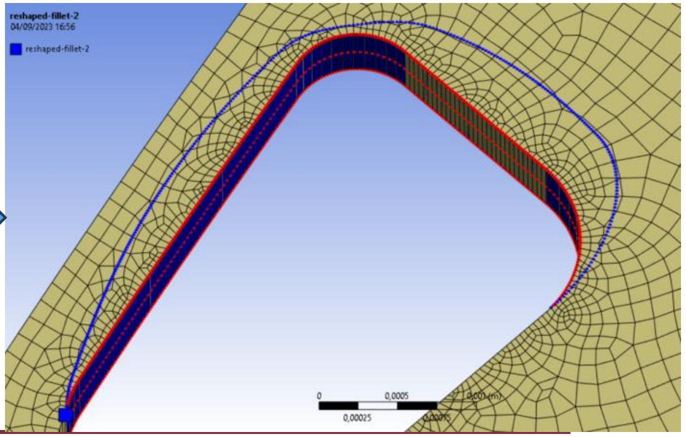
Point displacement



Fillet shape modification



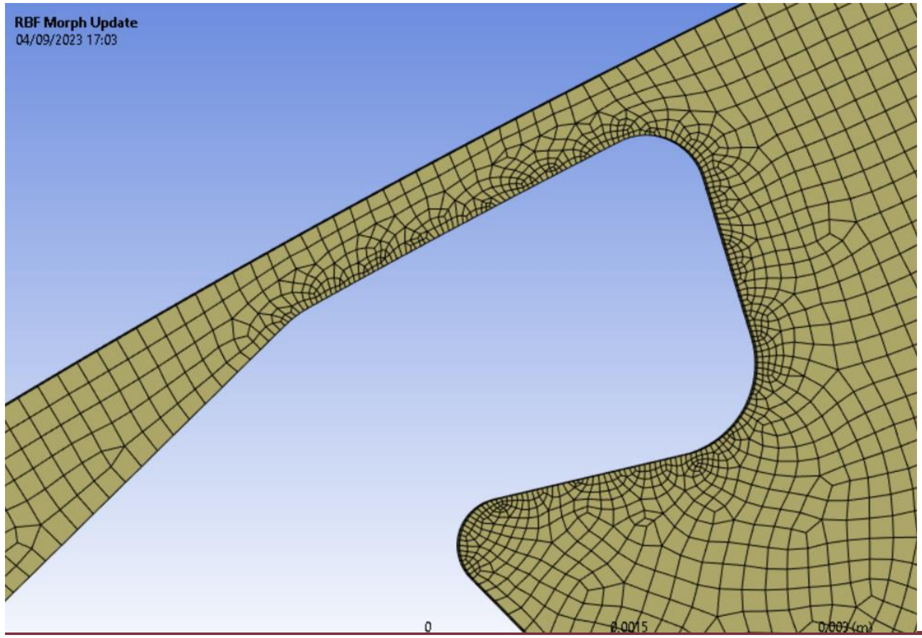
Magnet housing modification



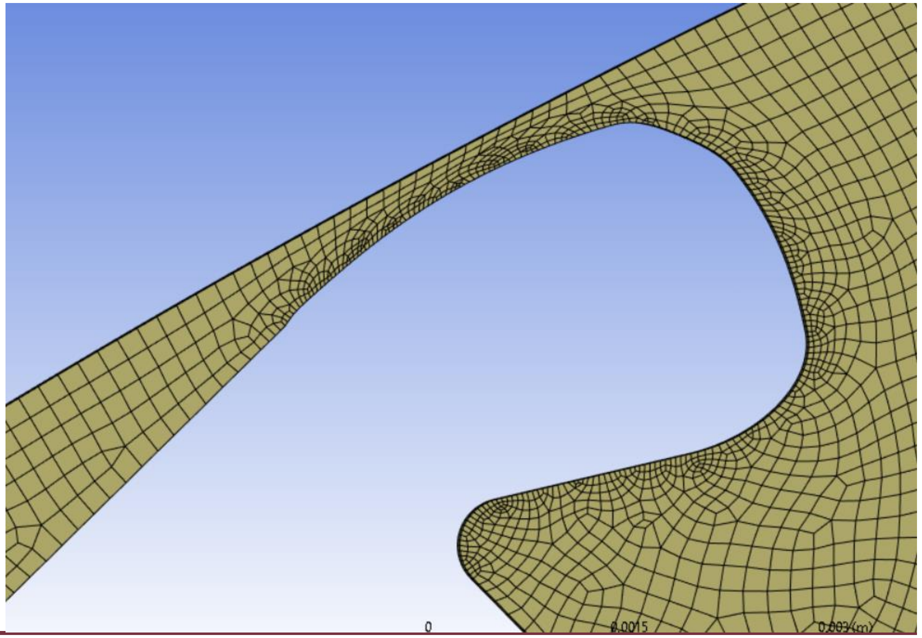
Parameter Based Optimization

- Constrained surfaces are kept fixed, as for the symmetry interfaces (both axial and planar)

Baseline configuration

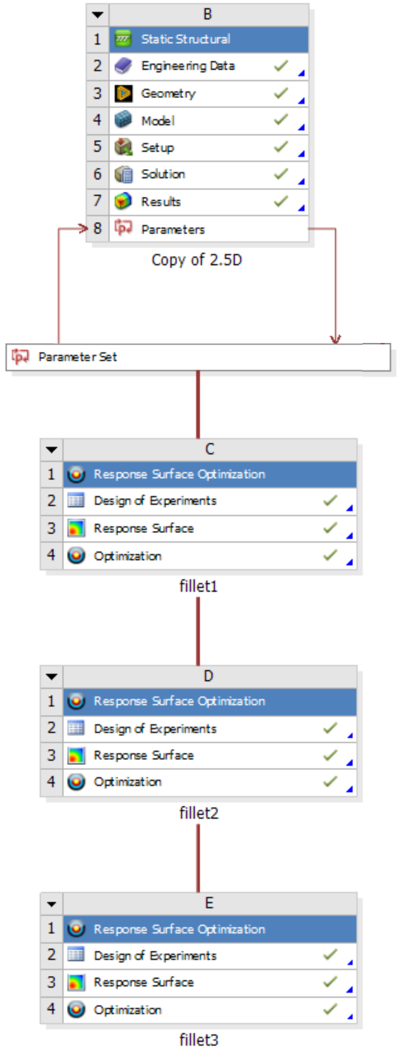


Morphed configuration



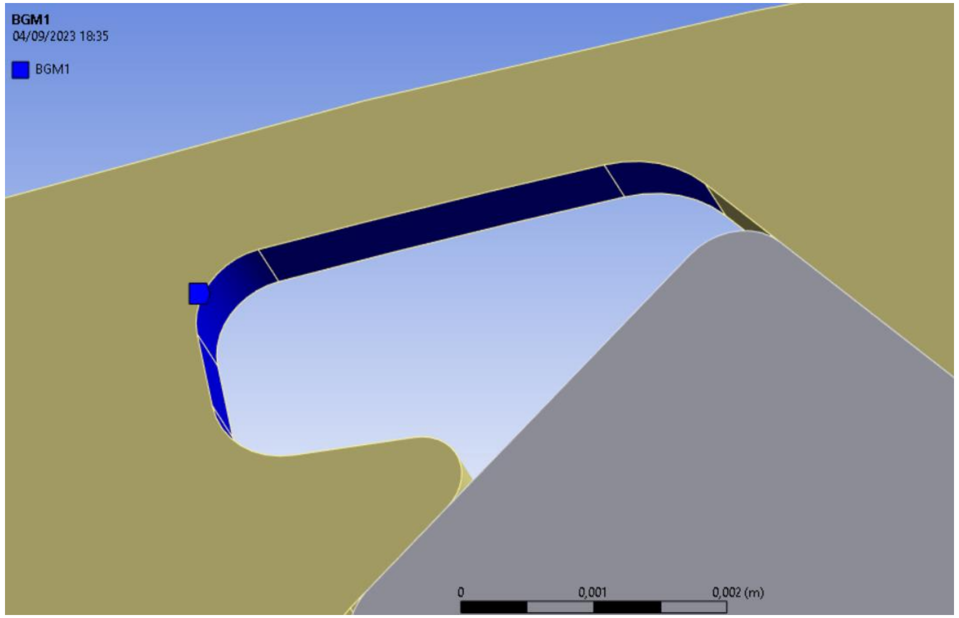
Parameter Based Optimization

- To perform the Parameter Based optimization 3 Response Surface Optimization were executed, acting on a single hot-spot separately
- Design Of Experiment (DOE) were set up using Latin Hypercube Sampling with CCD Samples, generating thus 15 Design Points (DP) for each hot-spot
- Response Surface type used was the Genetic Aggregation
- The optimization method used was the MOGA (Multi-Objective Genetic Algorithm)
- Each candidate point was finally re-evaluated, performing thus 48 FEM simulation to obtain an optimized configuration



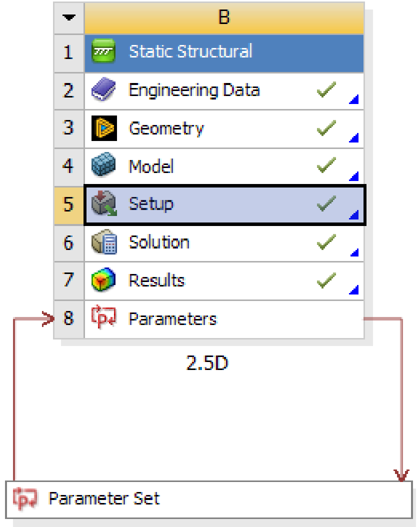
Parameter-Less Optimization

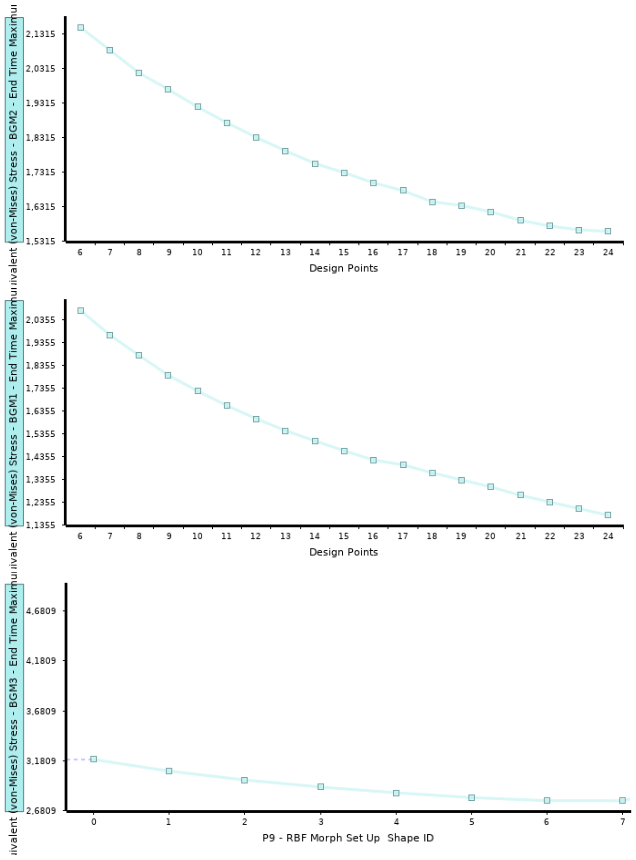
- In the Parameter-Less optimization, for each hot-spot an equivalent stress driven shape modification was applied
- For each hot-spot a maximum surface offset of 0.01 mm was applied
- An equivalent stress threshold of 200 MPa was used to define the inward and outward displacement



Parameter-Less Optimization

- The sequential morphing was performed exploiting the Parameter Set in ANSYS Workbench
- For 2 hot-spots 17 steps were performed, whilst for the third one the minimum value for the maximum equivalent stress was reached after 7 steps



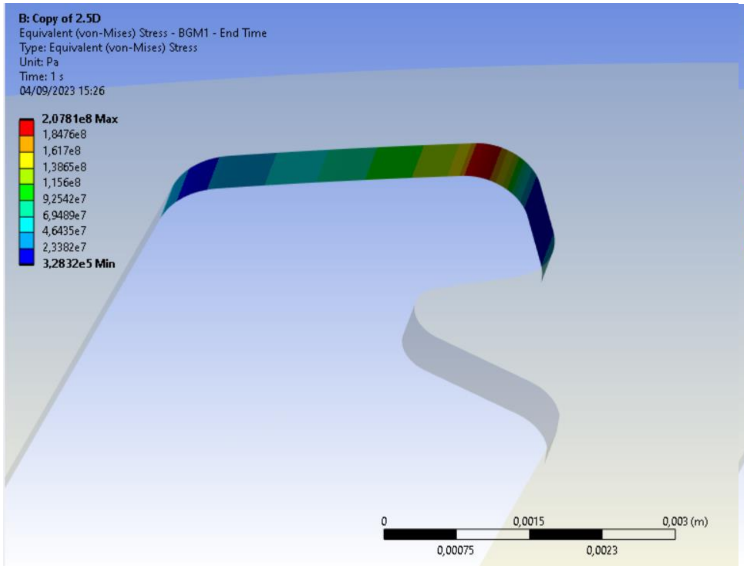


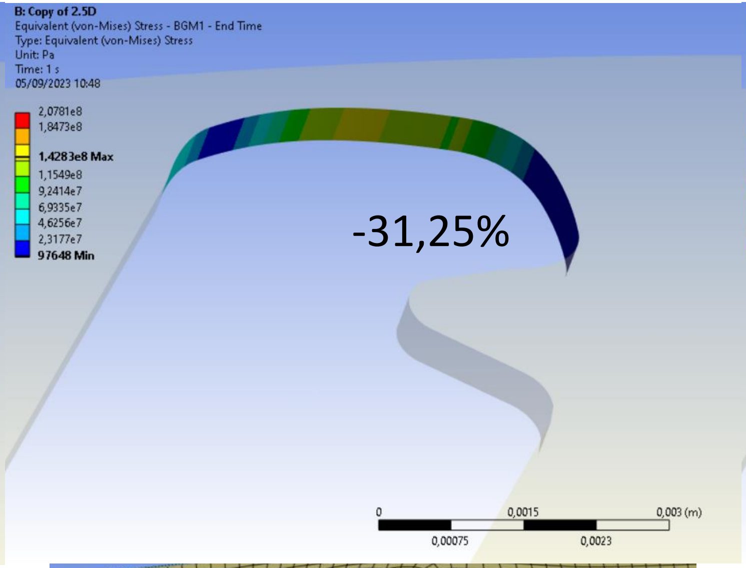
Optimization Results

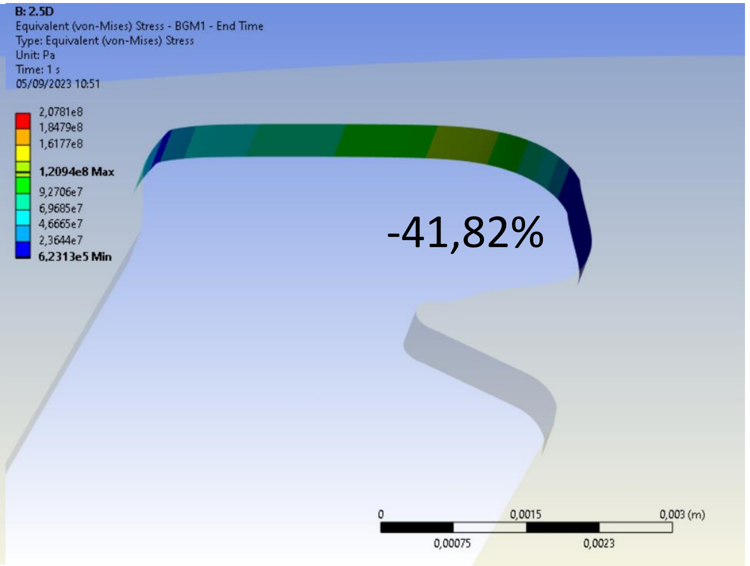
- Hot-spot 1

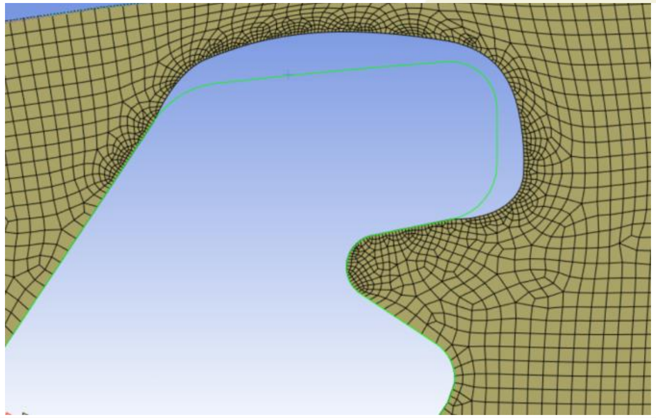
Parameter Based

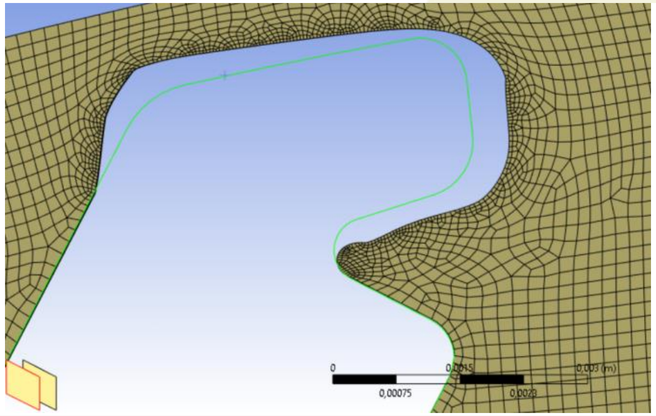
Parameter-Less







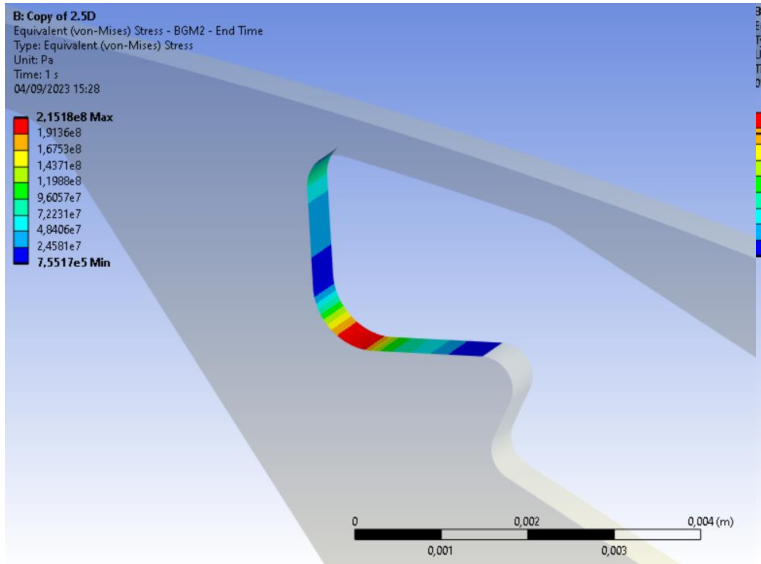


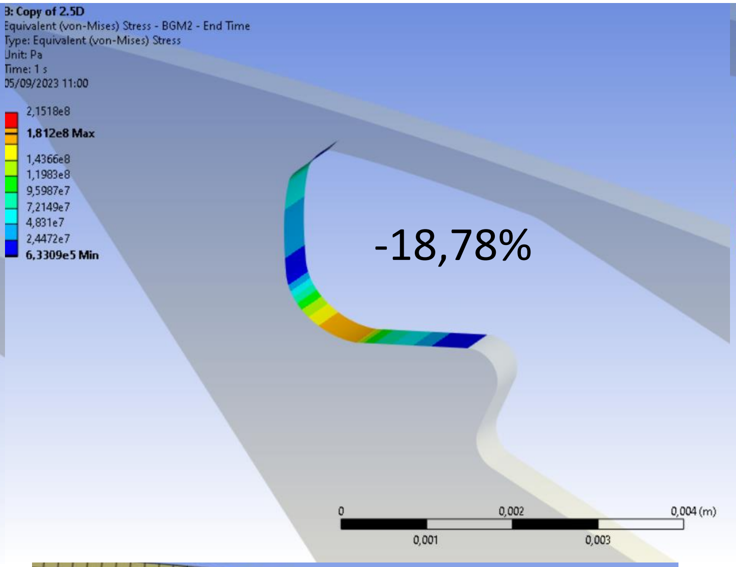


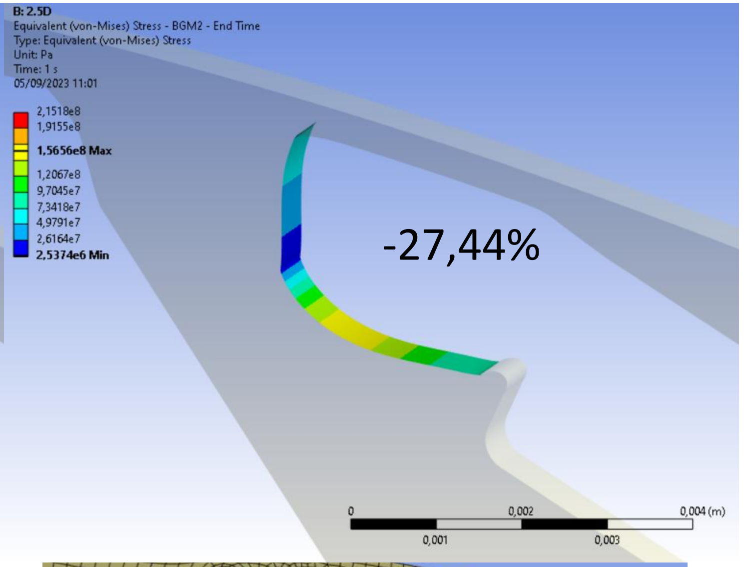
Optimization Results

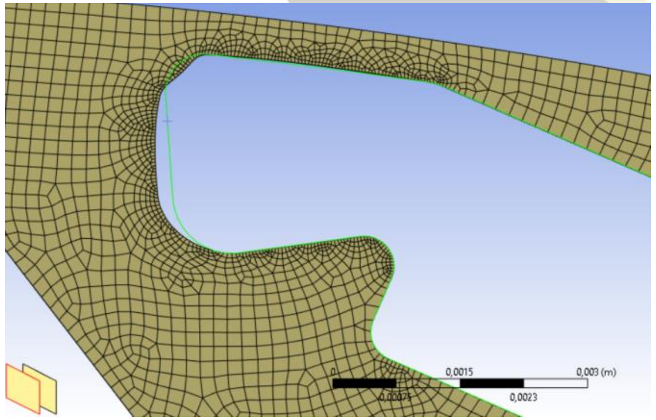
- Hot-spot 2

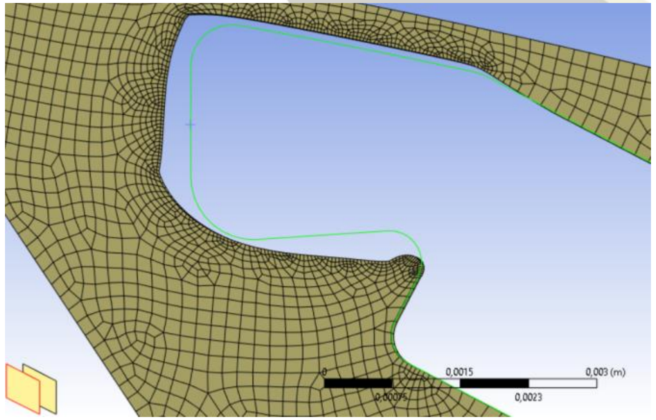
Parameter Based | Parameter-Less







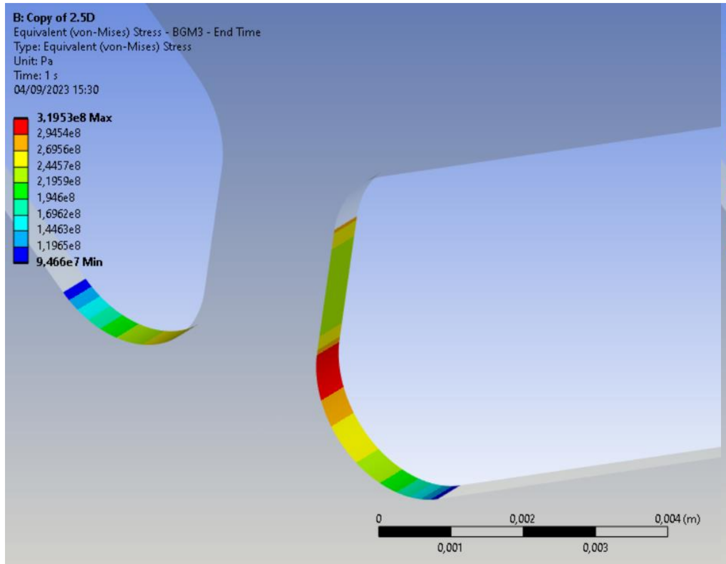


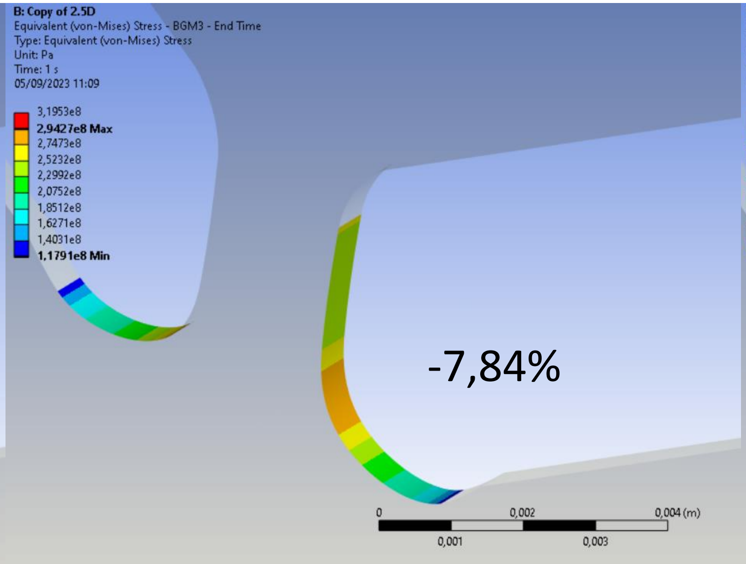


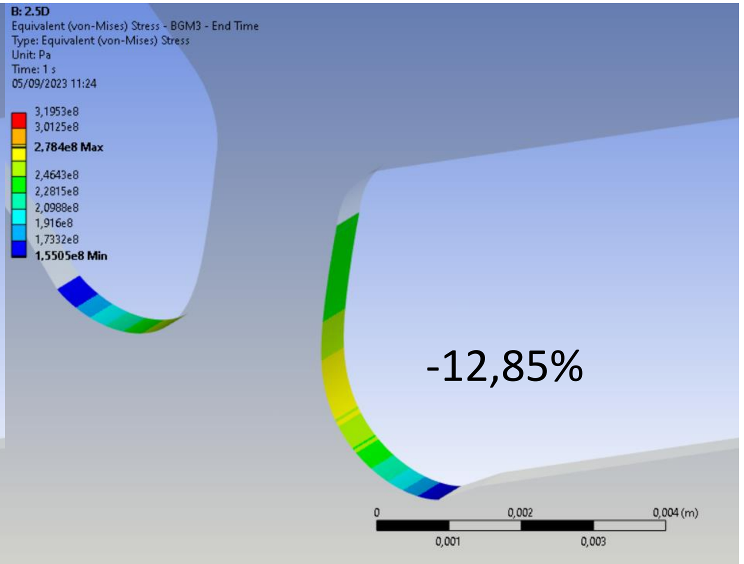
Optimization Results

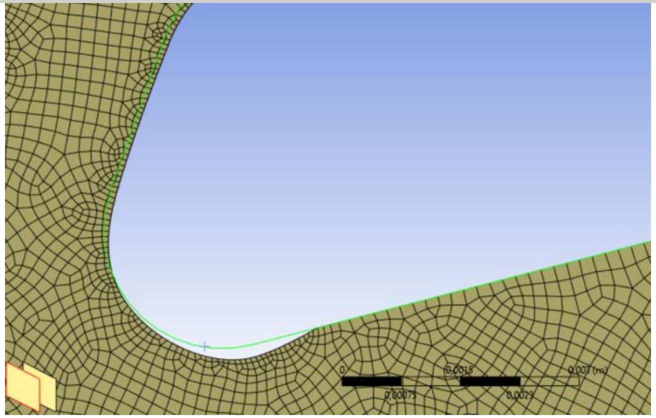
- Hot-spot 3

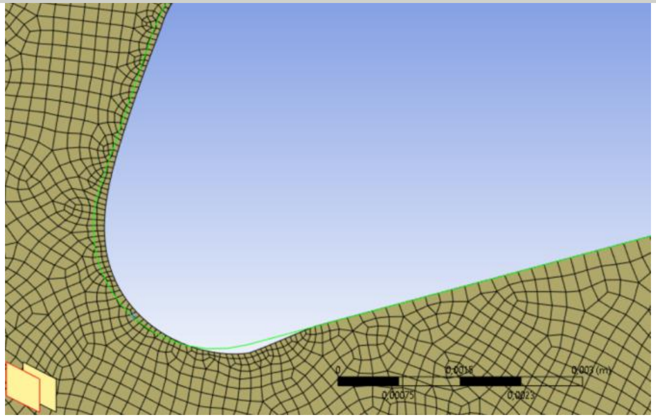
Parameter Based | Parameter-Less











Optimization Results

- Summary of Optimization Results:

	Baseline	Parameter Based		Parameter-Less	
Hot-spot 1	208 MPa	143 MPa	-31,25 %	121 MPa	-41,82 %
Hot-spot 2	215 MPa	181 MPa	-18,78 %	156 MPa	-27,44 %
Hot-spot 3	319 MPa	294 MPa	- 7,84 %	278 MPa	-12,85 %

Conclusions

- In the present work two optimization approaches for EM are presented, both based on RBF mesh morphing
- The application tested is a generic EM rotor in which three equivalent stress hot-spots were identified in the fillet region of magnet housing
- The first approach presented is the Parameter Based one: the hot-spots areas are made parametric by means of RBF mesh morphing
- The parametric model is then used in the DOE generation on which a response surface optimization tool is applied
- The second approach presented, the Parameter-Less one, combines the RBF based mesh morphing with the BGM, creating an automatic surface sculpting tool driven by surface stress levels

Conclusions

- Both approaches proven to be effective in reducing stresses in the identified hot-spots
- Stress reduction obtained with the Parameter Based approach on the three hot spots were respectively 31,25%, 18,78% and 7,84%
- Stress reduction obtained with the Parameter-Less approach on the three hot spots were respectively 41,825, 27,44% and 12,85%
- The Parameter Based approach optimization reached lower stress reduction rate at a higher computational cost: 48 FEM simulation were run, besides the response surface calculation cost. However optimized shapes results smoother if compared with ones obtained with the other approach
- The Parameter-Less approach required a lower computational cost (17 FEM simulation were run) to obtain optimized configuration

Conclusions

- The Parameter-Less approach required a lower computational cost (17 FEM simulation were run) to obtain optimized configuration
- Both approaches can be used in the complex multi-physics design of EM, since mesh morphing field evaluated to obtain the optimized shape can be used to morph other physic numerical models, in order to check if other EM requirement are meet and, eventually, iterate the design procedure

Thank You For Your Kind Attention!

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