Determination of Local Magnetic Material Properties using an Inverse Scheme

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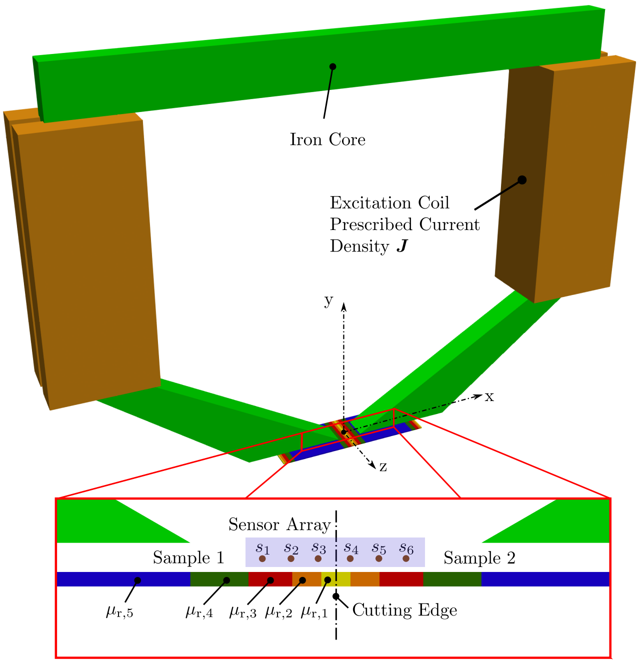
Introduction

In this work, the local magnetic material parameters of electrical steel sheets considering the influence of cutting processes [1] are determined. The methodology includes a sensor-actuator system, capable to locally excite and measure the magnetic flux density, numerical simulations and inverse schemes. In a first step, the measured data is artificially generated by solving the magneto-static problem with the finite element (FE) method using a 3D sensor-actuator system model. Furthermore, the samples under test (SUT) are divided into M subdomains, each assigned a searched-for linear isotropic magnetic permeability.

3D Sensor-Actuator System



Inverse Scheme I/II

The parameter vector $\boldsymbol{p}$ consists of M linear relative permeabilities $(\mu_{\mathrm{r},1}, \mu_{\mathrm{r},2}, \ldots, \mu_{\mathrm{r},M})^T$ and we solve the nonlinear least squares problem

$$\operatorname*{arg\,min}_{\boldsymbol{p}\in\mathbb{R}^n} \sum_{i=1}^{N_\mathrm{p}} \sum_{j=1}^{N_\mathrm{s}} \left\{ \frac{1}{2} \|\boldsymbol{F}_i(\boldsymbol{x}_j, \boldsymbol{p})\|_2^2 + \frac{1}{2}\alpha^2 \|\boldsymbol{p} - \boldsymbol{p}^{\mathrm{ref}}\|_2^2 \right\}$$

$$\text{s.t. } \nabla \times \frac{1}{\mu} \nabla \times \boldsymbol{A} - \boldsymbol{J} = \boldsymbol{0},$$

with $\boldsymbol{F}_i(\boldsymbol{x}_j, \boldsymbol{p}) = \boldsymbol{B}_i^{\mathrm{sim}}(\boldsymbol{x}_j, \boldsymbol{p}) - \boldsymbol{B}_i^{\mathrm{meas}}(\boldsymbol{x}_j)$, N_p the number of sensor-actuator positions, N_s the number of sensors, $\boldsymbol{B}_i^{\mathrm{sim}}(\boldsymbol{x}_j, \boldsymbol{p})$ the simulated magnetic flux density, $\boldsymbol{B}_i^{\mathrm{meas}}(\boldsymbol{x}_j)$ the measured magnetic flux density, α the regularization parameter (computed by Morozov's discrepancy principle), $\boldsymbol{A}$ the magnetic vector potential and $\boldsymbol{J}$ the electric current density.

Inverse Scheme II/II

The minimizer of the functional is computed via the quasi Newton scheme

$$\left(\mathcal{B}^T\mathcal{B} + \alpha_k^2 \boldsymbol{I}\right)\boldsymbol{q} = -\mathcal{B}^T \boldsymbol{F} - \alpha_k^2 \left(\boldsymbol{p}_k - \boldsymbol{p}^{\mathrm{ref}}\right)$$

$$\boldsymbol{p}_{k+1} = \boldsymbol{p}_k + \lambda \boldsymbol{q},$$

with $\boldsymbol{I}$ the identity matrix, $\boldsymbol{q}$ the search direction, $\boldsymbol{p}^{\mathrm{ref}}$ a priori information, λ the line search parameter (determined by Armijo rule) and $\mathcal{B}$ the approximated Jacobian using Broyden's update formula

$$\mathcal{B}_k = \mathcal{B}_{k-1} + \frac{1}{\boldsymbol{s}_k^T \boldsymbol{s}_k} \Big(\boldsymbol{F}(\boldsymbol{p}_k) - \boldsymbol{F}(\boldsymbol{p}_{k-1}) - \mathcal{B}_{k-1}\boldsymbol{s}_k \Big) \boldsymbol{s}_k^T$$

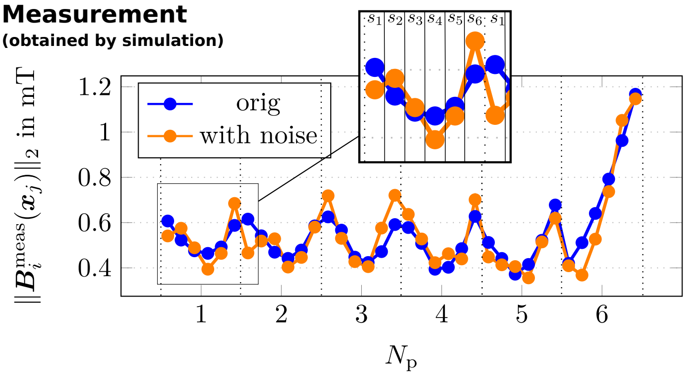
$$\boldsymbol{s}_k = \boldsymbol{p}_k - \boldsymbol{p}_{k-1}$$

Results

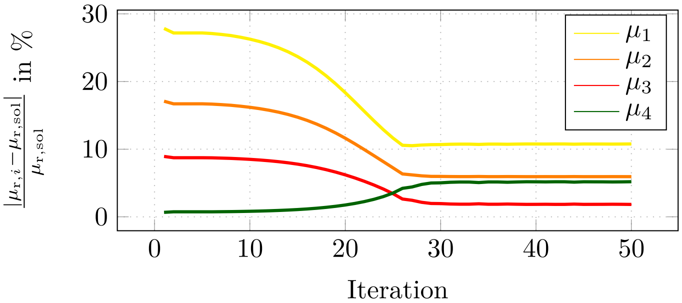
The artificially generated measurements are overlaid by a Gaussian white noise with 10% standard deviation and the following initial $\mu_{r,\mathrm{init}}$, reference $\mu_{r,\mathrm{ref}}$ and correct $\mu_{r,\mathrm{sol}}$ [2] relative permeabilities are assumed

Domain	Color Code	$\mu_{\mathrm{r,init}}$	$\mu_{\mathrm{r,ref}}$	$\mu_{\mathrm{r,sol}}$
1	yellow	499	1566	1225
2	orange	1776	3085	2635
3	red	3345	4300	3948
4	dark green	4391	4829	4862
5	blue	5000	5000	5000

Measurement
(obtained by simulation)



Convergency Behaviour



[1] M. Hofmann, H. Naumoski, U. Herr, and H.-G. Herzog, "Magnetic properties of electrical steel sheets in respect of cutting: Micromagnetic analysis and macromagnetic modeling," vol. 52, no. 2, pp. 1–14, Feb. 2016

[2] M. Bali, H. D. Gersem, and A. Muetze. "Finite-Element Modeling of Magnetic Material Degradation Due to Punching". In: IEEE Transactions on Magnetics 50.2 (Feb. 2014), pp. 745–748. doi: 10.1109/tmag.2013.2283967.

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