Inverse scheme to determine local variations of magnetic permeability

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Abstract First results of a research project aiming to identify locally the magnetic properties of cutted electric steel sheets are presented. In doing so, we provide the idea of a sensor-actuator system being able to excite and measure locally the magnetic field, and an inverse scheme based on solving the magnetic partial differential equations with the finite element (FE) method. First results are discussed, in which the measured data is obtained by a forward simulation and we restrict to locally varying linear magnetic permeabilities.

1 Introduction

For manufacturers of electric motors the precise knowledge of local magnetic properties and a model for accurately estimating the losses is of utmost importance for the design process [1], [2]. Current approaches to determine locally magnetic properties due to cutting effects can be found, e.g. in [3]. The goal of our research is the development of a combined method based on measurements, numerical simulations and inverse schemes to locally determine the magnetic properties of electric steel sheets. In a first step, we focus on the identification of the change of the linear permeability of steel sheets due to the cutting process. In doing so, we restrict to the 2D case and generate the measured data by forward simulations solving the magnetic field for the magneto-static case applying the finite element (FE) method. Based on these data, we apply our inverse scheme using the 2D simulation model, start at an initial guess of the permeability distribution and evaluate how accurate we can identify the different permeabilities in the steel sheet.

2 Computational setup

The sensor-actuator system consists of an iron core and an excitation coil, is able to scan the steel sheet, locally generate the magnetic field and measures it with a sensor array (see Fig. 1). The sensor array consists of Hall (measures the out of plane component of the magnetic field) and GMR sensors (measures the in-plane component of the magnetic field). For the investigation, we subdivide the steel sheet in M sub-domains, all of them having a different relative magnetic permeability $\mu_{\mathrm{r},i}$ (see Fig. 1). To obtain the measured data, the sensor-actuator system is positioned at different locations along the steel sheet and the magnetic field at all sensor positions is evaluated and stored. Figure 2 displays the magnetic flux density distribution and field lines for the case, when the sensor-actuator is positioned near the cutting edge of the steel sheet.

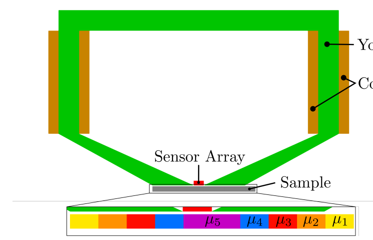

Fig. 1. 2D model of sensor-actuator system with multiple equidistantly distributed isotropic permeabilities. Please note that for the sake of better visualization, the sample thickness being 0.5 mm is enlarged by a factor of 10.

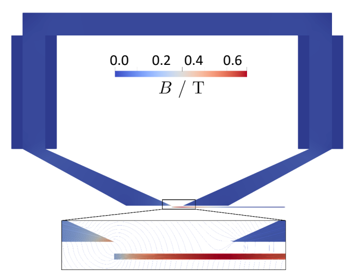

Fig. 2. Magnetic flux density distribution.

3 Inverse scheme

For our specific case, the parameter vector $\mathbf{p}$ consists of M relative magnetic permeabilities $(\mu_{\mathrm{r},1}, \mu_{\mathrm{r},2}, ..., \mu_{\mathrm{r},M})^T$, and the following nonlinear least squares optimization problem has to be solved

$$\min_{\boldsymbol{p}} \quad = \quad \frac{1}{2} \sum_{i=1}^{N} \left[\left(B_{\mathrm{x},i}^{\mathrm{meas}} - B_{\mathrm{x},i}^{\mathrm{FEM}} \right)^2 + \left(B_{\mathrm{y},i}^{\mathrm{meas}} - B_{\mathrm{y},i}^{\mathrm{FEM}} \right)^2 \right]$$
$$\text{s.t.} \qquad \nabla \times \frac{1}{\mu} \nabla \times \boldsymbol{A} = \boldsymbol{J} \,. \qquad (1)$$

In (1) $\boldsymbol{A}$ denotes the magnetic vector potential, $\boldsymbol{J}$ the current density in the coils of the actuator, B_i^{meas} the measured magnetic field values (obtained in our case by the forward simulation), and B_i^{FEM} the FE solution with assumed relative permeabilities $\mu_{\mathrm{r},j}$. Now, we may solve our identification problem by the least squares approach applying the quasi Newton method

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

$$\mathbf{p}_{k+1} \;=\; \mathbf{p}_k + \beta\mathbf{q}\,, \quad (3)$$

with $\boldsymbol{\mathcal{B}}_k$ an approximated Jacobian matrix of iteation k, $(\cdot)^T$ the transpose, α_k the regularization parameter, $\mathbf{I}$ the identity matrix and $\mathbf{q}$ the direction vector. The line search parameter β is determined by Armijo rule [4]. Broyden's method is utilized to estimate the Jacobian by applying rank-one updates computed by

$$\begin{aligned} \mathcal{B}_k &= \mathcal{B}_{k-1} + \frac{1}{\mathbf{s}_k^T\mathbf{s}_k}\left(\mathbf{F}\left(\mathbf{p}_k\right) - \mathbf{F}\left(\mathbf{p}_{k-1}\right) - \mathcal{B}_{k-1}\mathbf{s}_k\right)\mathbf{s}_k^T \\ \mathbf{s}_k &= \mathbf{p}_k - \mathbf{p}_{k-1}\,. \end{aligned} \quad (4)$$

4 Numerical results

The setup of the sensor-actuator system is displayed in Fig. 1 and the computed magnetic field for a specific position in Fig. 2. The sample is decomposed in 10 equidistant regions defining the unknown isotropic linear magnetic permeabilities μ_1, ... , μ_5 symmetrically distributed (see Fig. 1). As already mentioned, the measured magnetic field values at the sensors are performed by FE computations using the relative magnetic permeabilities as provided in Tab. I. In total, the forward simulations

TABLE I
REFERENCE PERMEABILITIES $\mu_{\mathrm{r},1}$, ..., $\mu_{\mathrm{r},5}$.

Permeabilities	$\mu_{\mathrm{r},1}$	$\mu_{\mathrm{r},2}$	$\mu_{\mathrm{r},3}$	$\mu_{\mathrm{r},4}$	$\mu_{\mathrm{r},5}$
Values [-]	1000	2000	3000	4000	5000

have been performed by positioning the sensor-actuator system at 5 different positions above the steel sheet and the measured magnetic flux densities at the sensor positions - both the x- and y-values - have been stored and used for the inverse scheme. As an initial guess, the average of the reference permeabilities is taken and multiplied with a small deviation factor (see Tab. II) to avoid a singular Jacobian matrix $\boldsymbol{\mathcal{B}}$ at the starting of the inverse scheme.

TABLE II
INITIAL PERMEABILITIES USED FOR THE INVERSE SCHEME.

Permeabilities	$\mu_{\mathrm{r},1}$	$\mu_{\mathrm{r},2}$	$\mu_{\mathrm{r},3}$	$\mu_{\mathrm{r},4}$	$\mu_{\mathrm{r},5}$
Values [-]	2985.0	2992.5	3000.0	3007.5	3015.0

As a stopping criterion of our inverse scheme, we compute the following norm

$$\epsilon = \sqrt{\frac{\sum_{i=1}^{N}\left(B_{\mathrm{x},i}^{\mathrm{meas}} - B_{\mathrm{x},i}^{\mathrm{FEM}}\right)^2 + \left(B_{\mathrm{y},i}^{\mathrm{meas}} - B_{\mathrm{y},i}^{\mathrm{FEM}}\right)^2}{\sum_{i=1}^{N}\left(\left(B_{\mathrm{x},i}^{\mathrm{meas}}\right)^2 + \left(B_{\mathrm{y},i}^{\mathrm{meas}}\right)^2\right)}}\,. \quad (5)$$

In doing so, the iteration is stopped after ϵ gets smaller than 10^{-4}, which is reached after about 10 iterations as

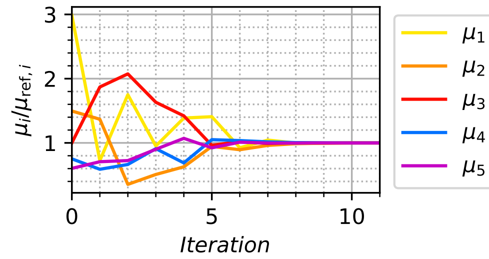

Fig. 3. Convergence behavior inverse scheme for each permeability μ_i.

displayed in Fig. 3. The number of line search iterations for each iteration k of the inverse scheme is shown in Fig. 4.

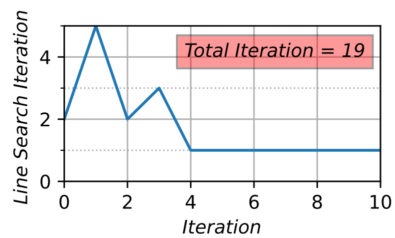

Fig. 4. Number of iterations of the line search for each iteration k of the inverse scheme.

5 Conclusion and outlook

We have successfully demonstrated the identification of local variations of the magnetic permeability in electric steel sheets. In a next step, we will investigate in the robustness of the inverse scheme by also applying noise to the measured data, which is currently obtained by a forward simulation. In addition, it is well known that the change of the magnetic properties towards the cutting edge is strongly located near the edge. Therefore, we will perform a strong subdivision near the cutting edge.

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