

Inverse scheme for the local determination of magnetic material properties of electric steel sheets near cutting edges

M. Kaltenbacher¹, A. Gschwentner¹, S. Ulbrich² and B. Kaltenbacher³

¹Graz University of Technology, Institute of Fundamentals and Theory in Electrical Engineering, Inffeldgasse 18, 8010, Graz, Austria
manfred.kaltenbacher@tugraz.at, andreas.gschwentner@tugraz.at

²Department of Mathematics, TU Darmstadt, Dolivostraße 15, 64293 Darmstadt, Germany
ulbrich@mathematik.tu-darmstadt.de

³Department of Mathematics, AAU Klagenfurt, Universitätsstrasse 65-67, 9020 Klagenfurt, Austria
barbara.kaltenbacher@aau.at

In order to better understand and model the various loss mechanisms that occur in electrical machines during operation, the actual degradation of electrical steel sheets due to cutting, punching, welding etc. is of paramount importance. In this contribution, we present a recently developed inverse scheme being capable to identify locally the degradation of the magnetic steel sheets due to the machining process. In doing so, the objective function, which penalises the difference between the measured and the simulated magnetic flux density, has to be minimised under a constraint defined according to the corresponding partial differential equation model. We use the adjoint method to efficiently obtain the gradients of the objective function with respect to the material parameters. Realistic numerical case studies show promising results.

Index Terms—Finite element analysis, inverse problem, local magnetic material behavior.

I. INTRODUCTION

In order to better understand and model the various loss mechanisms that occur in electrical machines during operation, the actual degradation of electrical steel sheets due to cutting, punching, welding, etc. is of paramount importance. In [1], the effects of three different cutting techniques, namely punching, waterjet and laser cutting, on the magnetic properties of grain oriented electrical steel sheets have been investigated and a loss model based on measurements (using an Epstein frame) has been developed. The result showed that the relative increase in core losses was in the range of 180% - 120%, 50% - 40% and 6% for laser, punching and waterjet cutting, respectively and demonstrates the importance to locally determine the change of the magnetic material properties. It should be noted that the problem at hand is quite complex as one can only measure the magnetic field quantities outside the steel sheets, i.e. the stray field. Therefore, the local determination of the magnetic material behavior requires the solution of an inverse problem.

II. PROBLEM SETUP

We assume an experimental setup as displayed in Fig. 1. The goal is to identify the magnetic material model, which may be linear, non-linear or even hysteretic, in each subdomain Ω_i , especially to find out how the magnetic properties change in the direction of the cutting edges. In doing so, we assume N_s sensors and N_p positions of the sensor-actuator system, and for each position, we excite the magnetic field from a minimum to a maximum over N_e excitation levels, and in the hysteretic case over many cycles with different excitation amplitudes. Therefore, the problem may be defined as follows

$$\min_{B \in V, \theta \in \mathbb{R}^{n_\theta}} J(B, \theta) \quad \text{s.t.} \quad \mathcal{A}(B, \theta) = 0 \quad (1)$$

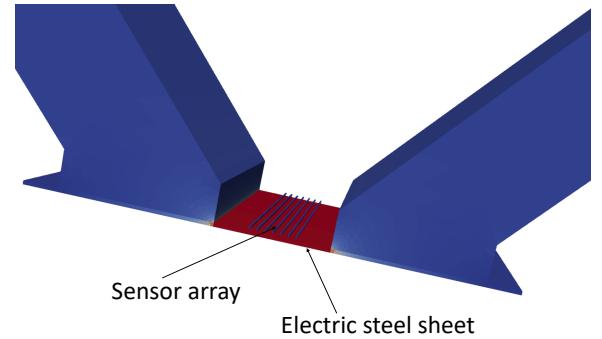


Fig. 1. Zoom into the sensor-actuator system displaying part of the electric steel sheet, the sensor array and the poles of the actuator.

with the objective function J , the model operator $\mathcal{A}$ defined according to the partial differential equation of magnetostatics, which has to be solved in order to get the magnetic flux densities B at the sensor positions and compare it with the measured values.

III. INVERSE SCHEME

To determine the local magnetic material properties, the overall inverse method includes the following steps:

- Perform measurements with an appropriate setup
- Solve the forward and adjoint problem by an efficient finite element solver [2]
- Compute the gradients of the objective function w.r.t. the material model parameters, which we perform by the adjoint method [3]
- Apply an efficient gradient based optimizer.

Thereby, the objective functional is defined according to

$$J(\mathbf{u}, \boldsymbol{\theta}) = \frac{1}{2} \sum_{p=1}^{N_p} \sum_{e=1}^{N_e} \sum_{s=1}^{N_s} \frac{1}{|\Omega_s^{\text{sen}}|} \int_{\Omega_s^{\text{sen}}} |\mathbf{B}_{p,e,s} - \mathbf{B}_{p,e,s}^m|^2 d\Omega + \underbrace{\alpha(\boldsymbol{\theta} - \boldsymbol{\theta}^{\text{ref}})^T \mathbf{D}(\boldsymbol{\theta} - \boldsymbol{\theta}^{\text{ref}})}_{\text{regularization term}}, \quad (2)$$

where Ω_s^{sen} is the domain of sensor s , $\mathbf{B}_{p,e,s} = \nabla \times \mathbf{u}_{p,e,s}$ is the computed magnetic flux density and $\mathbf{B}_{p,e,s}^m$ the measured one, $\mathbf{u}_{p,e,s}$ the computed magnetic vector potential, $\boldsymbol{\theta} = (\theta_1, \dots, \theta_{N_{\text{sd}}})$ the vector of parameters of the magnetic material model, $\boldsymbol{\theta}^{\text{ref}}$ the vector of reference parameters of the BH -curves and $\mathbf{D}$ a diagonal weighting matrix. Furthermore, $\mathcal{A} : V \times \mathbb{R}^{n_\theta} \rightarrow W$ is the model operator (defined according to the weak form of the PDE, including boundary conditions) with appropriate function spaces, V and W .

IV. RESULTS FOR THE NONLINEAR CASE

For the numerical investigation, a 0.5 mm thick electrical steel sheet is divided into 5 sub-regions (see Fig. 1). The sensor-actuator system is equipped with $N_s = 7$ Hall sensors (capable of measuring all three components of the magnetic field vector) evenly distributed along the straight line. The measured data $\mathbf{B}^{\text{meas}}$ is calculated numerically on a much finer computational grid than the one used for the inverse scheme. In addition, measurement noise (Gaussian white noise $\mathcal{N}(0, \sigma^2)$ with $\sigma = 10\%$) is superimposed on the computed data.

The results for the local identification of the non-linear BH -curves are shown in Fig. 2, where the colour yellow is the region closest to the cutting edge [3].

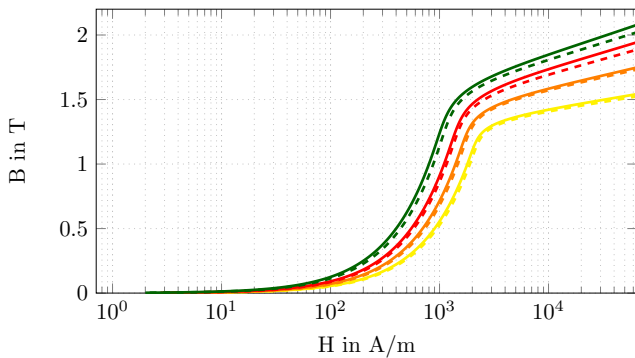


Fig. 2. BH -curves for $\boldsymbol{\theta}^{\text{exact}}$ (solid line) and $\boldsymbol{\theta}^{\text{opt}}$ (dashed line) for the different subdomains Ω_i .

V. CURRENT INVESTIGATION

Currently, we are extending our computational scheme to include the hysteretic behavior of the electrical steel sheets. The hysteresis operator is based on the dry friction-like vector

hysteresis model [4], which is fully thermodynamically consistent. To this end, the constitutive equation is written as

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}) = \mu_0\left(\mathbf{H} + \sum_{j=1}^N \omega_j \mathbf{M}_j\right) \quad (3)$$

with N the number of pinning fields, $\mathbf{M}_j$ the magnetization vector for each pinning field j , and ω_j the weighting factors, which need to be determined by the inverse scheme. According to our FE-formulation based on the PDE for the scalar magnetic potential [2], and assuming an isotropic material behaviour for the electric steel sheets, we may express the magnetic permeability by

$$\mu = \frac{|\mathbf{B}|}{|\mathbf{H}|} = \frac{\mu_0}{|\mathbf{H}|} \left(|\mathbf{H}|^2 + 2\mathbf{H} \cdot \sum_{j=1}^N \omega_j \mathbf{M}_j + |\mathbf{M}|^2 \right)^{1/2}. \quad (4)$$

To compute the gradient of the objective function w.r.t. the material model parameters, the derivative of the magnetic permeability μ w.r.t. the weighting factors ω_j is required. In doing so, we arrive at

$$\frac{\partial \mu}{\partial \omega_j} = \frac{\mu_0}{|\mathbf{H}|} \frac{\mathbf{H} \cdot \mathbf{M}_j + \mathbf{M} \cdot \mathbf{M}_j}{(|\mathbf{H}|^2 + 2\mathbf{H} \cdot \mathbf{M} + |\mathbf{M}|^2)^{1/2}}. \quad (5)$$

This result demonstrates the advantage of the dry friction-like vector hysteresis model, which allows an easy analytical differentiation of the objective function w.r.t. the searched for material model parameters. We are currently implementing (5) in our inverse scheme and will present the results at the conference.

ACKNOWLEDGMENT

The work is supported by the joint DFG/FWF Collaborative Research Centre CREATOR (DFG: Project-ID 492661287/TRR 361; FWF: 10.55776/F90) at TU Darmstadt, TU Graz and JKU Linz.

REFERENCES

- [1] R. Sundaria, A. Hemeida, A. Arkkio, A. Daem, P. Sergeant, A. Belahcen. Effect of Different Cutting Techniques on Magnetic Properties of Grain Oriented Steel Sheets and Axial Flux Machines. IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society, 2019 <https://doi.org/10.1109/IECON.2019.8926876>
- [2] L. D. Domenig, K. Roppert and M. Kaltenbacher. Incorporation of a 3-D Energy-Based Vector Hysteresis Model Into the Finite Element Method Using a Reduced Scalar Potential Formulation. IEEE Transactions on Magnetics, 2024 <https://doi.org/10.1109/TMAG.2024.3387354>
- [3] M. Kaltenbacher, A. Gschwentner, B. Kaltenbacher, S. Ulbrich, A. Reinbacher-Köstinger. Inverse Scheme to Locally Determine Nonlinear Magnetic Material Properties: Numerical Case Study. Mathematics 2024, <https://doi.org/10.3390/math12101586>
- [4] A. Sauseng, M. Kaltenbacher, K. Roppert. Revisiting the dry friction-like magnetic vector hysteresis model, Journal of Magnetism and Magnetic Materials, 2024, <https://doi.org/10.1016/j.jmmm.2024.172285>