

Determination of Local Magnetic Anhysteretic Behavior in Cut Electrical Steel Sheets using Local Measurements and an Inverse Scheme

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The accurate characterization of local magnetic properties in electrical steel sheets is critical for understanding material behavior and optimizing the performance in electrical machines. This study focuses on determining the local anhysteretic magnetic behavior near cutting edges, where material degradation significantly influences its material parameters. A high-precision measurement system is utilized to detect magnetic flux leakage (MFL) at cutting edges, followed by the application of an inverse scheme to compute the local magnetic material properties based on measured and simulated data. Results from a numerical case study demonstrate the feasibility of the proposed methodology.

Index Terms—Numerical simulation, inverse problems, ferromagnetic materials, magnetic field measurement.

I. INTRODUCTION

THE local magnetic properties of electrical steel sheets play a crucial role in the efficiency and reliability of electrical machines. In particular, the regions near cutting edges exhibit significant material degradation, resulting in altered magnetic behavior and increased losses [1]. Accurate characterization of these effects is essential both for the efficiency of the machine and its influences on the design process.

This work introduces a novel approach to determine the local anhysteretic magnetic behavior of electrical steel sheets in the vicinity of the cutting edge. A high-precision measurement system [2] is employed to capture magnetic flux leakage (MFL) profiles B^{meas} at cutting edges, which serve as input for the inverse scheme. Besides the measured data, numerical data B^{sim} is generated by solving the magnetostatic partial differential equation using an appropriate finite element model. Based on that, the local magnetic material properties are reconstructed using a gradient-based optimization procedure, whereby the gradient is computed by employing the adjoint method.

The proposed methodology is validated through a numerical case study [3], where artificially generated measurement data with noise is used to evaluate the approach.

II. MEASUREMENT SETUP

The measurement system is specifically designed for the high-precision detection of local magnetic flux leakage (MFL) at the cutting edges of electrical steel sheets. The system is generally mounted on a robust granite portal and comprises a X-Y table, which supports the magnetization unit, along with a linear precision measurement stage. A high-precision optical point sensor and a 3D Hall probe are mounted to the measurement stage via an adjustable mounting device (see Fig. 1).

The optical point sensor scans a predefined spatial grid to reconstruct the actual topology of the surface. Based on

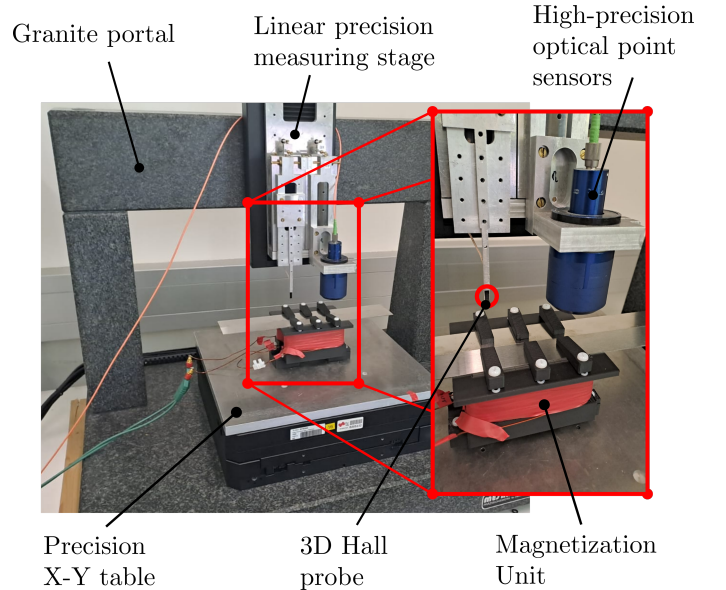


Fig. 1: Main components of the measurement system

this reconstruction, a reference coordinate system, xyz^{SUT} , is established (see Fig. 2) enabling the detection of minimal position deviations. Magnetization of the sheets perpendicular to the cutting edges, is achieved using a U-yoke constructed from ferrite cores. At the cutting edges, magnetic flux leakage (MFL) arises due to material degradation. The MFL profile is characterized by scanning with the 3D Hall probe at various spatial coordinates relative to the xyz^{SUT} coordinate system.

As an example, the measurement results of the magnetic flux leakage (MFL) in the x and z directions for two different cutting methods, obtained at a specific magnetization level, are presented in Fig. 3a and Fig. 3b.

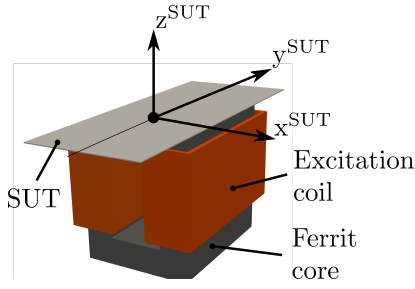


Fig. 2: Reference coordinate system for the measurements with two electrical steel sheets as sample under test (SUT)

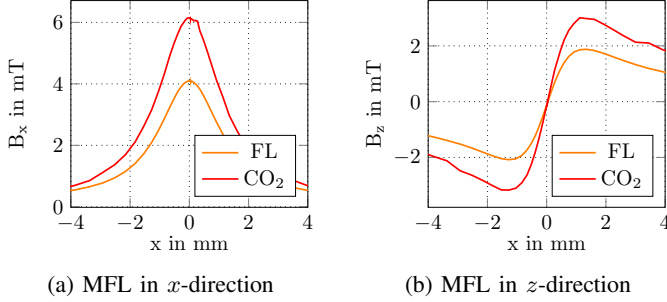


Fig. 3: Measured MFL for two different cutting methods (CO₂ laser and fibre laser (FL)) at specific magnetization level

III. INVERSE SCHEME

Since only the magnetic flux leakage (MFL) can be directly measured, an inverse problem must be solved to determine the local magnetic material properties. This problem is formulated as follows:

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

where J is the objective function, and $\mathcal{A}$ is the model operator corresponding to the partial differential equation of magnetostatics, which is solved to compute the magnetic flux densities $\mathbf{B}^{\text{sim}}$ at the measurement positions.

The general procedure for computing the local magnetic material properties involves the following steps:

- **Data acquisition** using the measurement setup described in Sec. II.
- **Solving the forward problem** for magnetostatics using an appropriate finite element model (see Fig. 2).
- **Gradient computation** using the adjoint method.
- **Optimization** of the described problem (1) using a gradient-based optimizer.

A numerical case study with a different measurement setup is provided in [3]. In this study, the electrical steel sheets are divided into 5 subdomains, with a high domain density near the cutting edge. The measurement data is generated artificially using the finite element method. To account for measurement noise, Gaussian white noise with a standard deviation of $\sigma = 10\%$ is added to the artificial data. Additionally, to avoid an inverse crime, a much finer mesh is used for generating the synthetic measurement data.

The results of the case study, showing the reconstructed nonlinear BH -curves, are presented in Fig. 4.

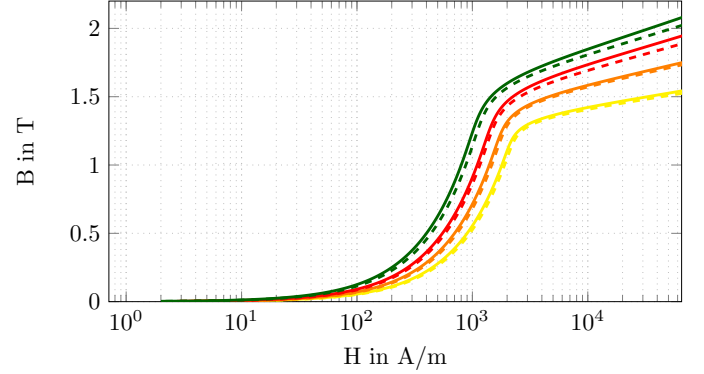


Fig. 4: Exact (solid line) and optimized (dashed line) nonlinear BH -curves for the different subdomains - Yellow: subdomain in the vicinity of cutting edge

IV. OUTLOOK

Currently, we are validating and optimizing the measurement setup to minimize measurement noise as well as positional deviations. After this calibration procedure, measurements are performed on isotropic electrical steel sheets used in electrical machines, considering various cutting techniques. The obtained measurement data are subsequently utilized in the inverse scheme (see Sec. III) to compute the local magnetic material properties. The findings from this investigation are presented at the conference.

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