

Implementation of a Phenomenological Anisotropy Model in Finite Element Code and Comparison with a Measurement-Based Model

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This paper explores the implementation of a phenomenological anisotropy model, which relies solely on measurements along the rolling and transverse directions, within a finite element method (FEM) simulation environment. Currently, grain-oriented laminations are widely used to enhance the efficiency of electrical machines, but their complex behavior demands accurate modeling. Nonlinear simulation for this model are performed on a simplify case of a transformer, and compared to a model based on measurements in equidistant angular steps without a phenomenological representation.

Index Terms—Grain-oriented materials, splines, magnetic anisotropy, nonlinear magnetics, finite element methods.

I. INTRODUCTION

EXTENSIVE research examines the use of grain-oriented electrical steel (GOES) to improve machine efficiency, even by a few percent. Renowned for superior magnetic performance in the rolling direction (RD) (high permeability and low magnetic losses), these steels are strategically employed to guide the magnetic flux along this preferred direction.

Due to their inherent texture, these laminations not only exhibit nonlinear behavior but also strongly anisotropic magnetic characteristics between the RD and the transverse direction (TD). To ensure an accurate efficiency evaluation before prototype development, it is crucial to account for the anisotropic behavior of these materials to properly estimate the losses.

This study presents an innovative implementation within the Finite Element Method (FEM) software code_Carmel [1] of the phenomenological model developed by Fiorillo [2], based on Neel's phase theory. The model assumes a perfect single-crystal structure, and proposes an evolution of the magnetic domains resulting from the contributions of two distinct domains, the 180° and 90° domains, respectively aligned along the RD and TD directions, depicted in Fig. 1. For a given induction, the model calculates the volume fraction between the two domains, providing the contributions. Neel's theory is applied to describe the internal field $\mathbf{H}_i = \mathbf{H} + \mathbf{H}_d$, which is the vector sum of the applied field $\mathbf{H}$ and the demagnetizing field $\mathbf{H}_d$. In simulations, the internal field is computed, meaning that the intrinsic properties of the material are directly considered, independently of any geometric considerations.

To this model, we combined a simplified implementation approach for anisotropic models based on spline function interpolation, as previously studied in [3] for other models. This approach is similar to the one used by Fujiwara [4], which integrated the model of Enokizono into an FE code using Bézier function interpolation. However, the disadvantage of this model is that it requires a large number of rotational field measurements, which are difficult to obtain as they rely on specialized measurement setups. Fiorillo model, on the other hand, has the advantage of relying solely on data along the RD and TD axes, which could allow for easier and more accurate modeling of any sheet material.

II. MAGNETIC ANISOTROPY MODELS

A. General expression of anisotropic models

Defining our models involves considering the local coordinate system of laminations (RD, TD, ND), with ND representing the normal direction to the laminations. The magnetic behavior of materials can be expressed through the reluctivity tensor ν . It establishes the relation between magnetic field and magnetic induction according to the relation $\mathbf{H} = \nu(\mathbf{B}) \mathbf{B}$.

The permeability along ND is assumed to be low and linear. This assumption allows us to decouple the magnetic behavior along ND. We also assume an anhysteretic behavior. The reluctivity tensor ν can be seen as a norm variation between H and B multiplied by an orientation variation. Moreover, as illustrated in [4], ν is expressed as a diagonal tensor, such that:

$$\nu = \nu_{\text{scal}} \begin{pmatrix} \cos \theta / \cos \beta & 0 \\ 0 & \sin \theta / \sin \beta \end{pmatrix} \quad (1)$$

with ν_{scal} the factor depending of the model, and θ, β the respective angles of $\mathbf{H}$ and $\mathbf{B}$ with respect to the RD.

B. The models

The magnetic behavior of GO is governed by distinct domain processes along the RD and the TD. In the demagnetized state, a regular pattern of 180° domains aligned with RD is observed, Fig. 1a. Along RD, magnetization reversal occurs via the motion of 180° domain walls, Fig. 1b. Along TD, magnetization involves 90° domain wall transformations, transitioning from 180° phases to coexisting 90° phases, Fig. 1c. This transition ends when β exceeds 45° with respect to the plane.

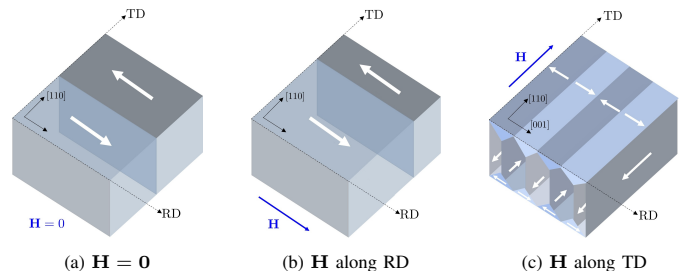


Fig. 1. Domain and wall structures in GO under applied fields: Comparison of RD and TD configurations emulating the ideal single-crystal case.

The magnetization of the 90° phase depends on its relative volume, v_{90} such that $J_{90} = v_{90} J_s \cos 45^\circ$ with $J_s = 2.02$ the polarization at saturation. For Fe-Si, the maximum J_{90} is $J_s/\sqrt{2} \approx 1.428$ T. It is therefore necessary to extend the model to include higher induction levels, which will be seen later.

In the following, we consider the polarization vector $\mathbf{J} \approx \mathbf{B}$. For a given (J, β) , his components are denoted by:

$$J_{180} = J \cos \beta, \quad J_{90} = J \sin \beta. \quad (2)$$

When considering the volume fractions $v_{180} = 1 - v_{90}$, the corresponding reduced polarization is given by:

$$J_{180}^{(r)} = J_{180}/v_{180}. \quad (3)$$

Based on measurements of the normal magnetization curves along the principal axes, expressed parametrically as $(H_{180}, J_{180}^{(r)})$ and (H_{90}, J_{90}) , the model allows the calculation of $\mathbf{H}_i$ of components H_{180} and H_{90} .

As mentioned earlier, the model is limited by $J_{90} < 1.428$. As done in previous works [3] and by Fujiwara [4], to facilitate the implementation and the derivative formulas in a FE code, the model is interpolated. Additionally, this technique allows to easily extend the model. According to expression (1), two interpolations are performed: one for the scalar factor ν_{scal} , another of the angle θ , both relative to the variables B and β . A representation of H_i and θ resulting from this interpolation is shown in Fig. 3. The bicubic Hermite splines interpolation is opted to ensure the monotonicity of the curves $\mathbf{H}(\mathbf{B})$.

As we know, at high fields the material behavior becomes isotropic. However, as the model approaches its limit, $\theta \rightarrow 0$, since $v_{180} \rightarrow 0$, $\mathbf{H}_i$ becomes dominated by its H_{180} component linked to $J_{180}^{(r)}$. Therefore, before θ drops below the angle β (see Fig. 3b), the model is extended such that at $H = 100$ kA/m according to Fig. 2, all curves merge, and $\theta = \beta$. Between these two states, splines are used to smoothly connect them.

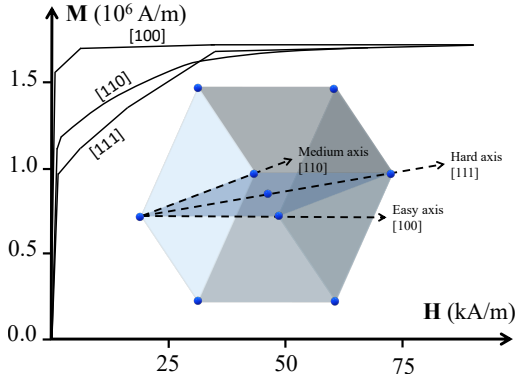


Fig. 2. Magnetization curves for a single crystal of iron.

For the comparative measurement-based model, the functional ν_{scal} result of the bicubic interpolation of the B–H curves for various angles, combined with an angle variation given by the mathematical law governing the angle variations of the elliptical-type models [3].

The angle variation of the measurement-based model is much smoother compared to Fiorillo model. However, the result obtained with Fiorillo model is very similar to the one in [4], where the interpolation of the norm and angle variation was directly performed using Enokizono model.

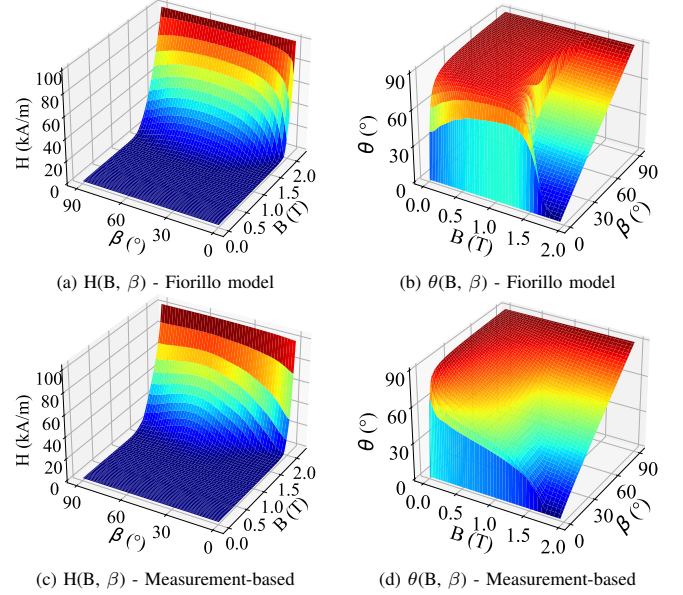


Fig. 3. 2D magnetization property of the two models.

III. APPLICATION

The modeled device is a transformer corner composed of four laminations, similar to those in an Epstein frame, arranged in two layers, stacked so that the upper lamination in the frame corner and the lower one have grain orientations perpendicular to each other. The 3D simulations were performed over a period at 50 Hz, with a sinusoidal excitation flux of $25 \mu\text{Wb}$, imposed between the two extremities, see Fig. 4. In an extended version, we will study other devices and simulate the losses.

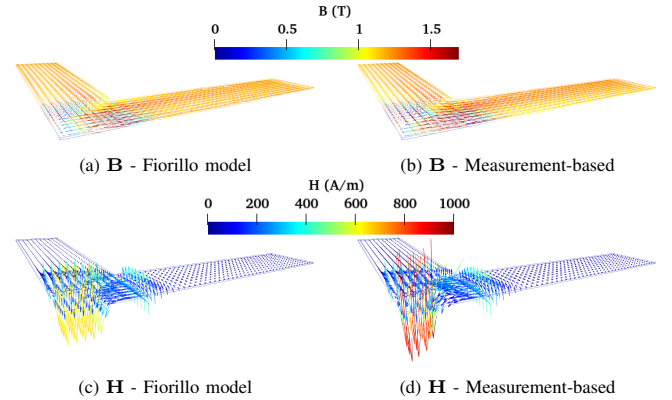


Fig. 4. $\mathbf{B}$ and $\mathbf{H}$ for an impose excitation flux of $25 \mu\text{Wb}$.

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