Determination of the reversible and irreversible magnetic field based on rotational single sheet measurements

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Keywords: Energy-based vector hysteresis, rotational magnetization, rotational losses, hysteresis measurement

Abstract

In this work, first results of the splitting of hysteresis measurements, performed with a rotational single sheet tester (RSST) into a reversible and an irreversible magnetic field component, are presented. This is of utmost importance for identifying parameters of energy-based vector hysteresis models because in their original formulation it is not possible to correctly depict vanishing rotational losses in full saturation. With the help of the proposed splitting of the measured magnetic field strength, new adaptions of the material model can be designed, which actually depict the underlying physical phenomena instead of just using a mathematical construct.

1 Introduction

In recent years, devices like power transformers and electric machines, which are already highly optimized appliances, need to be improved even further towards higher performance and efficiency, which shows the need of simulation tools, capable of correctly depicting local magnetic fields to evaluate, and later on, optimize global loss quantities, e.g., rotational losses. In order to correctly simulate these devices with, e.g., the finite element method (FEM), precise material models are needed, capable of incorporating hysteretic effects. One of the most promising set of vector hysteresis models are so-called energy-based models ([1], [2], [3]), where extensions like anisotropic behavior can easily be incorporated. The issue however, is the determination of model parameters for a specific material. Most measurements and identifications are carried out in a unidirectional setup with an Epstein frame or a single sheet tester [4]. This kind of identification however, neglects the inherent vectorial character of vector hysteresis, which manifests itself in an unsatisfying depiction of rotational losses, defined as

$$w_{\mathrm{rot}} := \int_0^{2\pi/\omega} \boldsymbol{b}(\boldsymbol{h}) \cdot \boldsymbol{h} \sin\theta\omega dt, \qquad (1)$$

where $\boldsymbol{b}$, $\boldsymbol{h}$ and θ are the magnetic flux density, field intensity and angle between $\boldsymbol{b}$ and $\boldsymbol{h}$ respectively. Measurements with a rotational single sheet tester (RSST), show vanishing rotational losses in full saturation, which

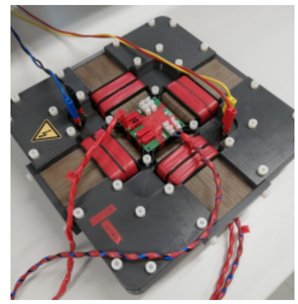

Fig. 1: Rotational single sheet tester used for measurements

energy-based vector hysteresis models can not depict without any adaptions.

In general, the losses in (1) can be decreased (and finally vanish) only if the irreversible field component (total field can be split into reversible and irreversible part $\boldsymbol{h} = \boldsymbol{h}_{\mathrm{rev}} + \boldsymbol{h}_{\mathrm{irr}}$) vanishes in full saturation or if the angle between $\boldsymbol{h}_{\mathrm{rev}}$ and $\boldsymbol{h}$ becomes zero (corresponds to angle θ in (1)). In this work, a RSST is used to perform measurements of an isotropic steel sheet and a splitting of the total magnetic field intensity into a reversible $\boldsymbol{h}_{\mathrm{rev}}$ and an irreversible component $\boldsymbol{h}_{\mathrm{irr}}$ is proposed. By doing so, the material model can be adapted in such a way that the rotational losses are depicted correctly. Furthermore, with this splitting, the question if the vanishing of $\boldsymbol{h}_{\mathrm{irr}}$ or the angle θ is responsible for the decrease of rotational losses, can be answered.

2 RSST Measurements

The RSST used for carrying out the measurements is depicted in Fig. 1 and the material under test is a $80\mathrm{mm}$ x$80\mathrm{mm}$ x$1.2\mathrm{mm}$ non-oriented isotropic steel sheet. The $\boldsymbol{b}$-field is measured via two coils in x- and y-direction through the sheet, and for the $\boldsymbol{h}$-field measurement, a 3D Hall sensor as well as x- and y- coils at the surface of the sheet are used.

In order to prevent any influences of eddy currents, the frequency of the rotating excitation $\boldsymbol{h}$-field, produced via x- and y- excitation coils (depicted in red in Fig. 1), is set to 1Hz. In Fig. 2, results of rotational RSST measurements are shown, which are used later on to perform the splitting into a reversible and irreversible field.

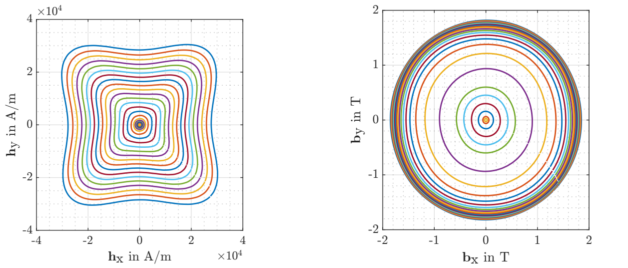

Fig. 2: $\boldsymbol{b}_\mathrm{x}/\boldsymbol{b}_\mathrm{y}$ and $\boldsymbol{h}_\mathrm{x}/\boldsymbol{h}_\mathrm{y}$ for increasing excitation

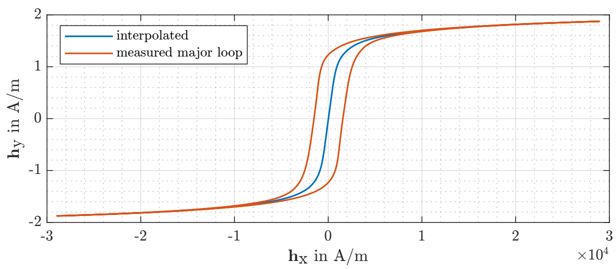

Fig. 3: Measurement of unidirectional $\boldsymbol{b}_\mathrm{x}$ and $\boldsymbol{h}_\mathrm{x}$ (equivalent to $\boldsymbol{b}_\mathrm{y}$ and $\boldsymbol{h}_\mathrm{y}$ since material is isotropic) with interpolated anhysteretic curve

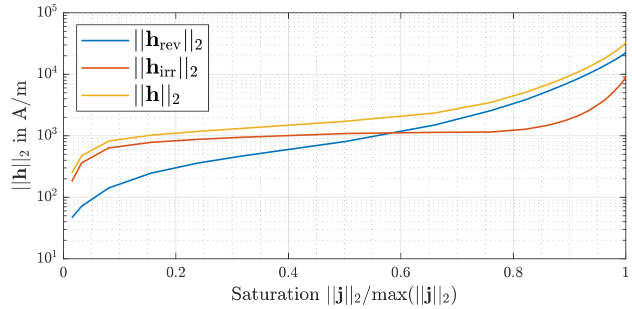

Fig. 4: Evolution of the irreversible and reversible field for rotational excitation with increasing amplitude

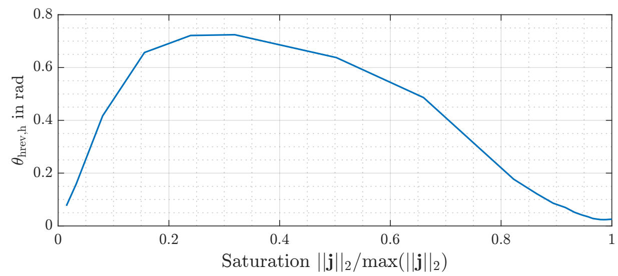

Fig. 5: Angle between $\boldsymbol{h}_\mathrm{rev}$ and $\boldsymbol{h}$ for rotational excitation with increasing amplitude

3 Proposed Splitting

The splitting of the $\boldsymbol{h}$-field is performed in three steps. First, the fact that only the reversible part contributes to the polarization $\boldsymbol{j}$ of the material ($\boldsymbol{j} = \boldsymbol{b} - \mu_0\boldsymbol{h}$), which is determined using the anhysteretic function $j_\mathrm{an}(\boldsymbol{h}_\mathrm{rev})$, is exploited, where the amplitude of the reversible field is denoted as $h_\mathrm{rev} = ||\boldsymbol{h}_\mathrm{rev}||_2$. This function can be easily obtained by performing unidirectional measurements of the major loop, depicted in Fig. 3. Secondly, the reversible component can be evaluated by inverting the anhysteretic function numerically and restating it as the minimization problem

$$h_\mathrm{rev} = \underset{h_\mathrm{rev}}{\operatorname{argmin}} \quad ||j_\mathrm{an}(h_\mathrm{rev}) - j^*||_2 \;, \tag{2}$$

where j^* is the measured magnitude of the polarization of the current time step. Finally, since the polarization always has the same direction as the reversible field, $h_{x,\mathrm{rev}}$ and $h_{y,\mathrm{rev}}$ can simply be obtained by multiplying its magnitude with the normalized direction vector of the polarization $\boldsymbol{e}_j$

$$\boldsymbol{h}_\mathrm{rev} = h_\mathrm{rev}\boldsymbol{e}_j \;. \tag{3}$$

The irreversible part can be obtained by using

$$\boldsymbol{h}_\mathrm{irr} = \boldsymbol{h} - \boldsymbol{h}_\mathrm{rev} \;. \tag{4}$$

Applying the proposed splitting technique to the rotational measurements in Fig. 2 with the anhysteretic curve based on the unidirectional measurements in Fig. 3, results in the behavior depicted in Fig. 4. In doing so, we can demonstrate that the irreversible field does not vanish in full saturation in the purely rotating case. With this result, the initial question from Sec. 1 can be answered. The reason for the vanishing rotational losses in full saturation can only be a result of the vanishing angle between $\boldsymbol{h}_\mathrm{rev}$ and $\boldsymbol{h}$, since the magnitude of $\boldsymbol{h}_\mathrm{irr}$ does not decrease. In order to verify this assumption, the angle between the measured $\boldsymbol{h}_\mathrm{rev}$ and $\boldsymbol{h}$ can be evaluated, which is depicted in Fig. 5.

4 Conclusion and Outlook

The first results obtained with the proposed splitting are very promising regarding their qualitative statement. However, for the full contribution, several materials must be measured in order to make sure that the proposed splitting holds true for different material compositions. In addition, the extension to the anisotropic case will be investigated.

Acknowledgements

The work is supported by the joint DFG/FWF Collaborative Research Centre CREATOR (CRC – TRR361/F90) at TU Darmstadt, TU Graz and JKU Linz.

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