

Rotational first-order reversal curves (rFORC) diagrams

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In recent years, there is a strong interest in the development of more efficient vector hysteresis models which can correctly describe the magnetization processes in ferromagnetic materials taking into account the vector nature of both applied field and magnetic moment. The scalar Preisach-type models complemented with the identification based on a set of first-order reversal curves (FORC) are typical examples of scalar hysteresis models which can provide accurate results in a large variety of cases. In the development of vector models the main difficulties are the numerical implementation and the lack of clear and tractable identification techniques. In this paper we are introducing a new type of measurement, a set of FORCs measured on the rotational hysteresis, and we are investigating it as a testing method for the vector hysteresis models performances.

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1. Introduction

The study of the magnetic processes taking place in real-world applications, like the processes behind the technology of magnetic information recording and storage or the magnetic behaviour of electrical machines, cannot neglect the vector character of both physical quantities involved – the magnetic field $\mathbf{H}$ and the magnetic moment $\mathbf{M}$.

The great variety of models for magnetic hysteresis can be included in two main classes:

- The *physical models*, from which category the micromagnetic models based on solving the Landau-Lifshitz-Gilbert [1] differential equations are one of the most widely used, are based on physical properties of the studied sample. The main strength of this kind of models is that their results can be easily linked with the physical parameters or causes.

- The *phenomenological models*, from which the Preisach model [2] is one of the most representatives, try to mimic the observed experimental behaviour using mainly mathematical tools, without necessarily using physical hypothesis. In this case the parameters of the model have no direct link with the physical properties of the sample.

In recent years, there is a strong interest in the development of more efficient phenomenological vector hysteresis models which can correctly describe the magnetization processes in ferromagnetic materials taking into account the complex vector nature of both applied field and magnetic moment.

The intense studies concentrated on scalar hysteresis have provided a number of models with reliable identification techniques which can explain a wide range of typical scalar measurements specific to most measuring

devices commonly available in the laboratories. The scalar Preisach-type models complemented with the identification based on a set of First-order reversal curves (FORC) is a typical example of a scalar hysteresis model [3] which can provide accurate results in a wide range of cases. Despite the success of the phenomenological models in the scalar hysteresis modelling, the development of vector models was not as successful, due to the difficult implementation of the different variants (e.g. [4], [5]) or due to the lack of clear and tractable identification techniques. This is one of the reasons why the most successful approach in the modelling of the vector magnetic behaviour is still the full micromagnetic (physical) approach. However, the main disadvantage of applying a micromagnetic model to large systems is that it requires huge computing resources so, in this context, phenomenological vector models represent a possible solution to get the required accuracy with high numerical efficiency

The most widely used strategy for designing phenomenological vector models is to enhance a scalar model by adding the angle of the applied field with respect to certain defined directions on the sample as input parameters. In the case of Preisach-type models, the calculus is taking in consideration a distribution of magnetic entities with different coercive and magnetic interaction fields, called Preisach function. The entities are associated with a straightforward geometric representation, the Preisach plane, which can give a clear image of the evolution of a system when the magnetic field changes. The Preisach-type models are usually generalized to vector models by adding an angular dependence to the scalar Preisach function [4].

One of the first tests that a vector generalization of a scalar Preisach-type model should pass is the simulation of major hysteresis loop branches, for any orientation of the

external field, without changing the values of the distributions' parameters, but by changing the angle of the applied field. Most vector models are passing this test [4-7]. The second numerical experiment largely used for the validation of a vector phenomenological model is the study of its response to rotational fields in different forms: rotational hysteresis losses, locus of magnetization vector tip etc.

In this paper we are evaluating the possibility to use a new tool for testing the vector models. This is based on the observation that the scalar FORC diagram is very sensitive to differences between experimental and model results. The idea is to use this property and to extend the concept of first-order reversal curve from the typical scalar hysteresis loop, to the rotational hysteresis. As this type of experiment can be easily performed in many laboratories we think this could also become a valuable characterization tool for the vector properties of a given ferromagnetic material.

In the next Section we shall present the models which are tested with this method, then, in Section III the rotational FORC diagrams are defined. Finally we present the results and conclusions

2. The models

One of the most well known vector models – the Mayergoyz vector Preisach model [4] – can be represented as a continuous superposition of scalar Preisach models of hysteresis. The total magnetization is computed using the following formalism:

$$\mathbf{M}(t) = \int_{-\pi/2}^{\pi/2} \hat{\phi} \left(\iint_{\alpha > \beta} P(\alpha, \beta, \varphi) \hat{\gamma}_{\alpha\beta} [\mathbf{H}(t) \cdot \hat{\phi}] d\alpha d\beta \right) d\varphi \quad (1)$$

where $\hat{\phi}$ is the unit vector along the direction specified by polar angle φ , $P(\alpha, \beta, \varphi)$ is the vector angular dependent Preisach distribution function, $\mathbf{H}$ is applied magnetic field, and $\hat{\gamma}_{\alpha\beta}$ are the rectangular hysteresis operators with α and β being the upper and lower switching values, respectively.

Mayergoyz also introduced – for classical scalar Preisach model [3] – a complete identification procedure based on a set of first-order reversal curves (FORC). The procedure is involving the computation of a second order mixed derivative of the magnetization curves to obtain the Preisach function and it wasn't used by experimentalists mainly due to the problems arising from performing a second order mixed derivative on real data. Lately, Pike [8, 9], introduced a robust interpolation algorithm that made possible the identification of the FORC distribution from experimental data, which in the case of systems correctly described by the classical Preisach model is identical to the Preisach function.

In a previous paper [10] we have presented a complete implementation of the Mayergoyz vector Preisach model and an identification algorithm based on a set of scalar

FORCs measured systematically for different angles between the global easy axis of the magnetic system and the applied field direction.

We have used a different strategy to develop a new vector model with a remarkable numerical efficiency related to the fact that can be easily implemented on parallel computer environments [11]. Essentially, our model, referred to as the Preisach-LLG model, uses the concept of vector pseudo-particle for which the equilibrium state in a given applied field is calculated with the well known Landau-Lifshitz-Gilbert algorithm. The main difference between our model and a classical micromagnetic model is that in our model the value of the interaction field acting on a pseudo-particle is considered fixed, like in the Preisach-type models. A statistically stable vector distribution of interaction fields is taken into account and this makes possible the de-coupling of the differential equations describing the magnetic behaviour of each pseudo-particle.

The module of the interaction field acting on each pseudo-particle is fixed and it is linked to the interaction field distribution similar to the one in the classical scalar Preisach model. Nevertheless, at the beginning there was no clear strategy to evaluate the direction of the interaction field vector. There are two main options:

1. a fixed direction – which can be chosen to be the easy axis direction of the system (the 0° direction) or the direction of each pseudo-particle's easy axis, or
2. a direction that can change, like the direction of the total magnetic moment $\mathbf{M}$ or the direction of the external field $\mathbf{H}$.

The first test problem we have described above – the simulation of the experimental major hysteresis loop (MHL) branches for any angle of the external field – gave no clear answer. The Preisach-LLG model was able to fit the data using both approaches for the interaction field direction mentioned above. Consequently, we directed our attention towards finding a rotational method for the validation of vector models.

3. The rotational first-order reversal curves (rFORC)

The measurement of a classical FORC starts like a regular MHL branch: the magnetic field is decreased from a large saturating value. Then, at a certain field, called *reversal field* H_r , one starts varying the field back towards saturation and the magnetic moment is measured. A set of first-order reversal curves is obtained by changing the value of the reversal field (Fig. 1(left)).

On the other hand, the *rotational hysteresis loop* can be experimentally obtained in the following sequence of fields:

- First, one saturates the sample on one direction, and then the field is decreased to a certain value.
- The field is maintained at a constant value and it is rotated 360° .
- For a set of values of the rotation angle the projection of the total magnetic moment on the field direction is measured.

- The field is then rotated back 360° towards the initial direction measuring the same projection. Usually, for values of the external field smaller than the saturation field the magnetic moment does not follow the same path and thus a rotational hysteresis loop is obtained.

In the same manner as FORC, we have measured *rotational FORCs* by starting one branch of the rotational hysteresis. Instead of rotating the field for 360° and back we have reversed the rotation direction after a certain value of the angle, called *reversal angle* θ_r , and we have measured the curve while rotating the field back towards 0° . The set of rotational FORCs in Fig. 1(right) is obtained by rotating a field equal to the coercive field of the sample (measured on 0° direction) and by changing the value of the reversal angle from 0° to 360° .

In both cases, the diagrams (Fig. 2) are obtained by derivation of the projection of the total magnetic moment on the field direction in function of (H, H_r) for FORC and of (θ, θ_r) for rFORC:

$$\rho(H, H_r) = -\frac{\partial^2 m(H, H_r)}{\partial H \partial H_r}, \quad \rho(\theta, \theta_r) = -\frac{\partial^2 m(\theta, \theta_r)}{\partial \theta \partial \theta_r} \quad (2)$$

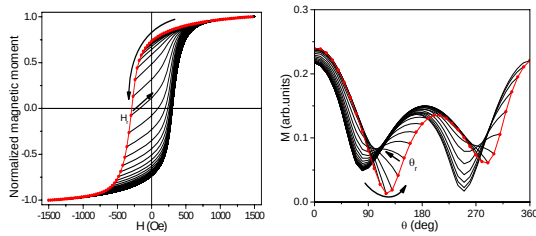


Fig. 1. An experimental set of first-order reversal curves (left) and rotational first-order reversal curves (right).

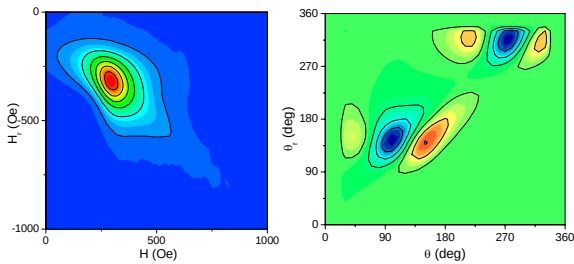


Fig. 2. The regular FORC diagram (left) and the rotational rFORC diagram (right).

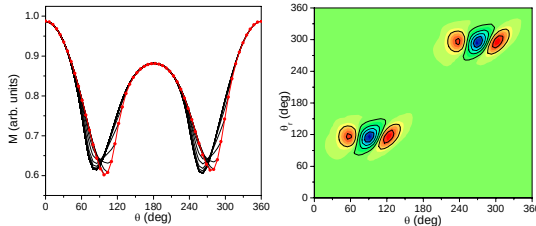


Fig. 3. Simulated rFORC using a micromagnetic model and the corresponding rotational FORC diagram.

4. Results

Fig. 1(right) presents the rotational hysteresis curve obtained on an oriented commercial magnetic tape sample as well as the FORCs - with θ_r one denotes the values of the angle for which the reversal of the rotation direction takes place. Fig. 2(right) shows the experimental rotational FORC diagram.

The experimental rFORC diagram shows a typical double set of characteristic structure, each containing a negative region between two positive regions. The structure is seen twice due to the symmetry present in the measurement technique. Thus one can assume that only one structure could be characteristic for the material.

To clarify this assumption, we have used a micromagnetic model to simulate the rFORC and the results are shown in Fig. 3. One can easily observe the similarity of both simulated rFORC curves and the resulting diagram with the experimental ones.

The micromagnetic model, being a physical model, includes the vector behaviour of both $\mathbf{H}$ and $\mathbf{M}$ in an intimate manner and – from this point of view – it was used in engineering applications as well as a tool in many types of theoretical studies (e.g. the statistic study of interactions in particulate media [12] or the study of the transverse susceptibility method [13]). Thus, the good agreement between measured and simulated rFORC diagram confirms once again the accuracy of the micromagnetic model.

In order to verify which direction would represent a better choice for the interaction field (H_i) in phenomenological vector models we have used the rFORC method on three different cases: LLG-Preisach model with H_i acting on a fixed direction or on a variable direction and classical vector Preisach model

If in our LLG-Preisach model one simulates the rFORC curves by rotating a magnetic field equal to the 0° coercive field while the interaction fields act on each particle on the 0° direction (the system's easy axis direction), then one obtains the rotational characteristics presented in Fig. 4. One can remark that the rFORC diagram presents more complex features which weren't encountered in any simulation made with the micromagnetic model or in experimental measurements.

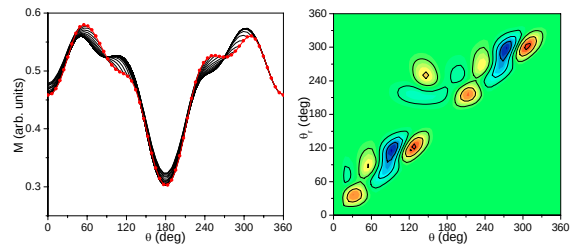


Fig. 4. Simulated rotational FORCs using LLG-Preisach model with the interaction fields acting on the 0° direction (left) and the rFORC diagram (right).

If, on the other hand, one considers the interaction field acting on the total magnetic moment $\mathbf{M}$ direction, than the characteristics of the rFORC diagram are very similar to the experimental case as can be seen in Fig. 5.

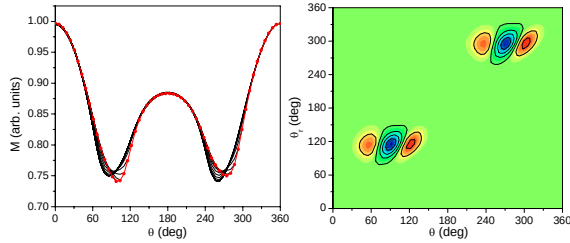


Fig. 5. Simulated rotational FORCs using LLG-Preisach model with the interaction fields acting on $\mathbf{M}$ direction (left) and the rFORC diagram (right).

If for the interaction field one chooses other fixed direction (e.g. interaction field acting on each pseudoparticle's easy axis) the results are similar to the one presented in fig. 4 while if one chooses other variable direction (e.g. interaction field acting on $\mathbf{H}$ direction) than results similar to the one presented in fig. 5 are obtained.

This leads to the idea that the feed-back mechanism in the scalar moving Preisach model [14], where H , the input of the model, is considered to be an algebraic sum of the external applied field and a mean field produced by the sample itself ($H = H_{ext} + \alpha M$), could be generalized to vector models in a simpler manner than the one proposed in [5], by considering that the interaction field direction changes together with $\mathbf{M}$ direction.

This is also confirmed by the results of similar simulations performed using the classical vector Preisach model, where the interaction field is considered to act on a fixed direction (Fig. 6).

4. Conclusions

In this paper we have proposed a new method – a set of FORCs measured on the rotational hysteresis – as test tool for vector hysteresis models performances.

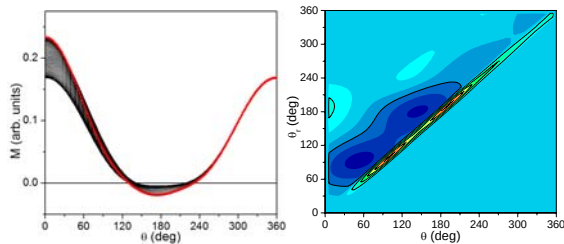


Fig. 6. The rFORC diagram obtained using vector Preisach model.

We have shown that the rFORC diagram can be used to identify the best choice for the direction of the interaction field. We have observed that the use of any fixed direction gives results which are very different from the experimental or micromagnetic ones in both LLG-Preisach and Mayergoyz vector model. On the other hand, if the direction of the interaction field is following the direction of $\mathbf{M}$ during the magnetization processes then the rotational properties of the model are drastically improving.

This concept could be considered as a vector generalization of feed-back idea in the scalar moving Preisach model.

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