Using Experimental FORC Distribution as Input for a Preisach-Type Model

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In this paper, we present a method of using the experimental first-order reversal curves (FORC) distribution as input for Preisach-type models. In order to be able to calculate in the model the integral over the FORC distribution we designed an interpolation algorithm of the three-dimensional (3-D) distribution. The algorithm is validated for a simple case—the output of a classical Preisach model—and then is used for realistic, asymmetrical FORC distributions. Several Preisach-type models are tested for the same FORC distribution and it is shown that the PM2 model gives the best results in simulating magnetization curves starting from the FORC diagram.

***Index Terms*—Magnetic hysteresis, magnetic materials, magnetization processes, modeling.**

I. Introduction

PHENOMENOLOGICAL approach to magnetic modeling is able to give good results in a much shorter time and demanding lesser computing performance than the physical (micromagnetic) approach.

The first-order reversal curves (FORC) method was introduced by Mayergoyz [1] as a method to identify the Preisach distribution [2] of a system which can be fully described by the classical Preisach model (CPM). In CPM, a particulate magnetic system is characterized by two independent statistical distribution of coercive and interaction fields. Mayergoyz proved that, in order to be correctly described by a CPM, the system should obey to the wiping out and congruency properties [1]. While most of the real systems meet the terms of the wiping-out property, the congruency property was hardly ever verified on real systems.

The lack of experimental systems which can be correctly described by CPM determined the evolution of many more realistic Preisach-type models—one of the most widely used is the generalized moving Preisach model which adds to the CPM hypotheses the reversible component of the magnetization processes and a mean field interaction term. In the same time, the interest in the FORC method diminished, especially because of the numerical errors introduced by the second-order derivative of the experimental data requested by this method of identification.

Recently, Pike *et al.* [3] introduced a versatile numerical method of evaluation of the FORC diagram starting from measured data. They also have separated the method from its origin—the CPM—and suggested to use it only as an experimental tool which can give information about magnetic systems. Since then, a considerable work has been undertaken in the field of the experimental FORC diagram interpretation.

The aim of parameter identification in Preisach modeling is to find algebraic functions which, when used as input for the model, fit the experimental observations and are able to predict sample's magnetic behavior. The main point in measuring FORCs and in the calculation from these experimental data FORC diagrams is especially related to the evaluation of interaction and coercive fields of the magnetic entities contained in a sample and to the evaluation of the ratio between the reversible and the irreversible magnetization processes. However, it was recognized by all those who are currently using this experimental method that the FORC diagram, even it is closely related to the well known Preisach distribution [2] (of coercive and interaction fields as well as the reversible distribution) is not identical to this distribution. It has been shown [4] that for real systems the interaction field distribution is changing as a function of the magnetic state so the FORC diagram should be seen like an averaged photography of a moving distribution.

It is important to emphasize that ideally, if an experimental FORC is used as the Preisach distribution in a CPM, the set of first-order reversal curves should be properly simulated. However we have shown in [5] that if we measure a set of second-order reversal curves we obtain a different diagram while the CPM will give a diagram identical with the FORC diagram. As in many cases we have observed that the differences are not too important, this gave us the idea to implement a Preisach-type model which uses the experimental FORC distribution as Preisach distribution and to analyze the quality of the predictions made by this model.

II. The Model

To obtain a point on the FORC starting on the descending branch of the major hysteresis loop (MHL), the following field sequence is applied to the sample: (H_m, H_r, H), where H_m is a field sufficient to saturate the sample, H_r, named reversal field, is a field in the domain $(-H_m, H_m)$ and H is the actual field at which the sample magnetic moment—noted with $m^{-}_{\mathrm{FORC}}(H, H_r)$—is measured; the sign minus is indicating that the FORC is measured on the descending branch of MHL. The FORC distribution is given by the second-order mixed derivative

$$\rho(H, H_r) = -\frac{1}{2}\frac{\partial^2 m^{-}_{\mathrm{FORC}}}{\partial H \partial H_r} \tag{1}$$

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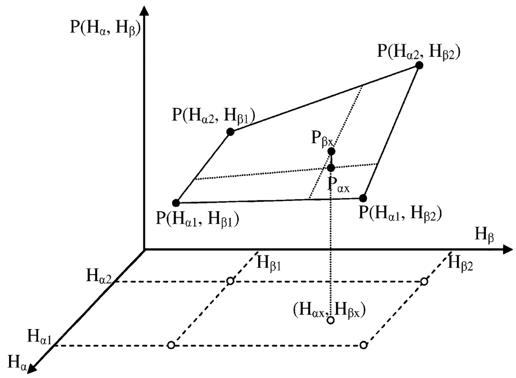

Fig. 1. Algorithm for the interpolation of the FORC diagram.

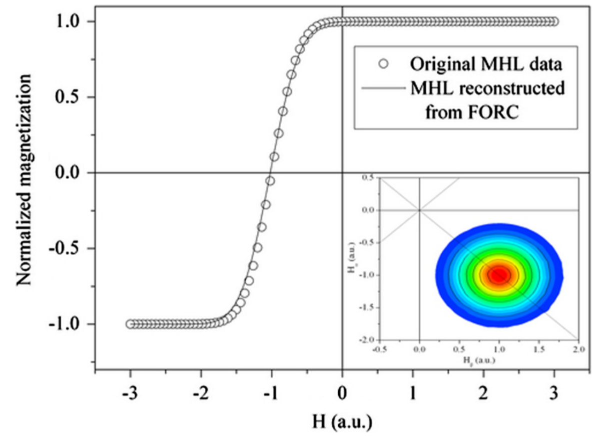

Fig. 2. Original MHL descending branch obtained with a CPM (with circles), the FORC diagram obtained from the same model (in insert) and the MHL descending branch obtained by using the FORC as input distribution for another CPM (with line). (Color version available online at http://ieeexplore.ieee.org.)

and the FORC diagram is the contour plot of this distribution. For the descending branch of MHL the (H, H_r) coordinates correspond to the (H_β, H_α) coordinates of the Preisach plane, in this order. To integrate the FORC distribution, which is known in a number of points in (H_α, H_β) coordinate system, to calculate the magnetic moment in a certain magnetization process one must find a possibility to find an approximate value of the diagram in each point of the Preisach plane.

We propose a simple and numerically efficient interpolation algorithm for the approximation of the FORC diagram in any point (Fig. 1). Let us assume we want to calculate the numerical value of $P(H_{\alpha x} H_{\beta x})$. One starts from the coordinates values of four known points making a three-dimensional (3-D) generalized rectangle—$P(H_{\alpha 1}, H_{\beta 1})$, $P(H_{\alpha 1}, H_{\beta 2})$, $P(H_{\alpha 2}, H_{\beta 1})$, $P(H_{\alpha 2}, H_{\beta 2})$—with the condition that $[H_{\alpha 1}, H_{\alpha 2}]$ and $[H_{\beta 1}, H_{\beta 2}]$ are the smallest intervals including $H_{\alpha x}$ and $H_{\beta x}$, respectively. Using two sets of two linear interpolations one obtains the values $P(H_{\alpha x}, H_{\beta 1})$, $P(H_{\alpha x}, H_{\beta 2})$, $P(H_{\alpha 1}, H_{\beta x})$, and $P(H_{\alpha 2}, H_{\beta x})$. Further on, after another two linear interpolations one obtains two values—$P_{\alpha x}(H_{\alpha x}, H_{\beta x})$ and $P_{\beta x}(H_{\alpha x}, H_{\beta x})$—for the arbitrary field values $(H_{\alpha x}, H_{\beta x})$. The value of the distribution is then approximated as the average of these two values: $P(H_{\alpha x}, H_{\beta x}) = (P_{\alpha x} + P_{\beta x})/2$.

Using this algorithm as input for a CPM one can obtain the magnetization curves of the system used in FORC measurements.

In order to test the interpolation algorithm, first we generated a FORC diagram using a set of first-order reversal curves obtained from a classical Preisach model with analytic Gauss distributions for both coercive and interaction field and then we used the diagram as input for the same type of model.

The results, presented in Fig. 2, demonstrate, as expected, a very good agreement between the original ("experimental") and the calculated data. The differences between the two curves can be associated to the numerical errors made during the two stages of the algorithm.

- First, at the calculus the FORC diagram from the original data where one uses an interpolation of the original data using a second degree polynomial function as described in [3].
- Second, at the interpolation of the discreet FORC diagram using the algorithm described in this paper.

III. Asymmetrical FORC Distributions

Most of the real systems show symmetry of the experimental magnetization curves. That includes symmetry, with respect to the origin of the (H, m) system, of the MHL and of the FORCs measured on the descending and ascending branches of the MHL. For a CPM system, when this symmetry of the magnetization curves is observed, we expect to obtain the same FORC distribution form both ascending and descending FORCs. Furthermore, the FORC distribution, identical to the Preisach distribution, is also symmetrical with respect to the coercivity axis in the Preisach plane. For CPM systems, asymmetrical FORC/Preisach distributions can be obtained only for systems showing asymmetrical magnetization curves. One have to mention that even in this case ascending and descending FORC distributions are identical. However, in most cases asymmetrical FORC diagrams are obtained for systems showing symmetrical magnetization curves. This is a clear indication of a non-CPM systems and this problem has to be addressed in order to improve the quality of the Preisach simulation.

For most of the experimental systems one obtains FORC distributions which are asymmetrical (sometimes highly asymmetrical) with respect to the second diagonal of the coordinate system (the coercive field axis). This leads to an important problem: if one would use this kind of experimental FORC distribution as input for a CPM one would obtain an asymmetrical major loop—MHL with different shapes of upper and lower branches.

In this paper, we will address only the case, observed in many magnetic materials, which have symmetric magnetization curves but asymmetric FORC distributions.

For them, there are two main sources of asymmetry.

- The presence of a mean field interaction term which can be represented as a moving term that shifts the distribution in the Preisach plane when the total magnetization changes [6].
- The asymmetry in reversible magnetization—at a certain field value, the slopes of the upper and the lower hysteresis

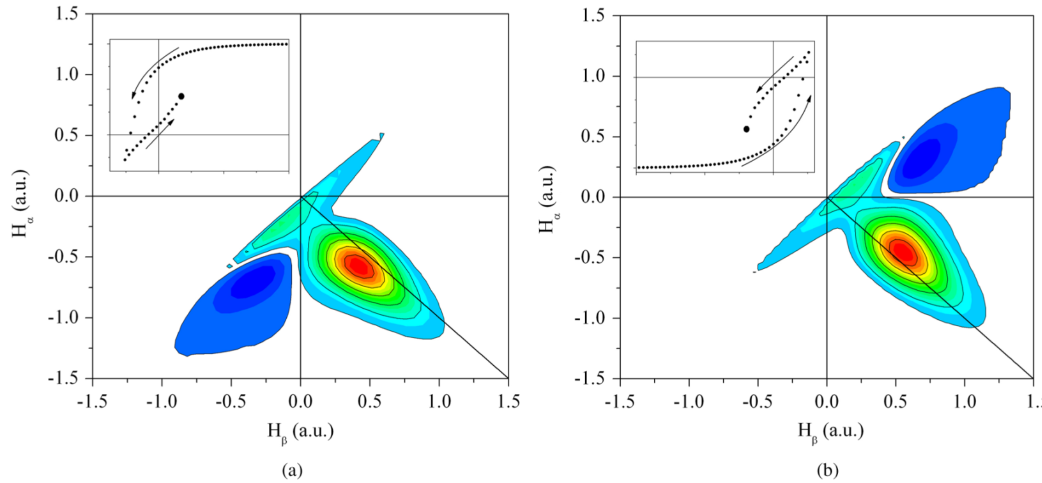

Fig. 3. FORC diagrams for the same sample when the reversal curves are measured (a) towards positive saturation and (b) towards negative saturation. (Color version available online at http://ieeexplore.ieee.org.)

branches are not equal, not even for a single domain particle if the angle of the applied field is different than 0 or $\pi/2$.

The shape of the FORC diagram is, in this case, dependent on the direction of which reversal of the field takes place so one can obtain two different diagrams, mirrored with respect to the second diagonal of the coordinate system (Fig. 3).

For a more realistic approach we propose to use both diagrams in an algorithm similar to the one designed by us for the PM2 model. The PM2 model is an advanced Preisach type model which includes results from systematic observations of interaction field distribution evolution during magnetization processes of different types of magnetic systems. The model uses a dual interaction field distribution which changes as function of the magnetic moment. It has been proven [4] that the PM2 model includes both mean interaction field and variable variance effects as particular cases.

If the FORC diagram measured starting from reversal points found on the descending major hysteresis branch is $P_{\text{down}}(H_\alpha, H_\beta)$ [Fig. 3(a)] and the diagram measured starting from reversal points found on the ascending major hysteresis branch is $P_{\text{up}}(H_\alpha, H_\beta)$ [Fig. 3(b)], then the Preisach-type model should receive as input distribution

$$P = \frac{(1+M)}{2} \cdot P_{\text{down}} + \frac{(1-M)}{2} \cdot P_{\text{up}}. \tag{2}$$

Fig. 4 shows in insert the FORC diagram from Fig. 3(a). The distribution has been used as input for a CPM and for a PM2 type model. One can see that the PM2 type model gives excellent results even with asymmetrical FORC distribution as input.

IV. Conclusion

We have described a new interpolation algorithm which allows the evaluation of a given discrete 3-D distribution in any point. We have used this algorithm for introducing a FORC diagram as input for Preisach-type models.

We have shown that the PM2-type algorithm gives very good results in simulating magnetization curves even when starting from asymmetric FORC distributions.

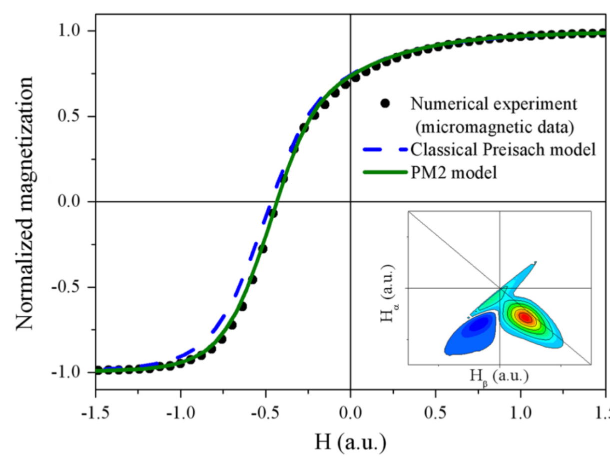

Fig. 4. Comparison of two results—from a generalized Preisach-type model and a PM2 model—with experimental data. In insert the irreversible FORC distribution and the reversible distribution used as input for the models. (Color version available online at http://ieeexplore.ieee.org.)

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References

[1] I. D. Mayergoyz, *Mathematical Models of Hysteresis*. New York: Springer-Verlag, 1990.

[2] P. Preisach, "Über die magnetische Nachwirkung," *Zeitschrift für Physik*, vol. 94, pp. 277–302, 1938.

[3] C. R. Pike, A. P. Roberts, and K. L. Verosub, "Characterizing interactions in fine magnetic particle systems using first order reversal curves," *J. Appl. Phys.*, vol. 85, pp. 6660–6667, 1999.

[4] A. Stancu, L. Stoleriu, P. Postolache, and R. Tanasa, "New preisach model for structured particulate ferromagnetic media," *J. Magn. Magn. Mater.*, vol. 290-291, pp. 490–493, 2005.

[5] A. Stancu, L. Stoleriu, and P. Andrei, "Magnetic characterization of samples using first and second order curves diagrams," *J. Appl. Phys.*, vol. 99, no. 1, 2006, 08D702.

[6] A. Stancu, C. R. Pike, L. Stoleriu, P. Postolache, and D. Cimpoesu, "Micromagnetic and preisach analysis of the FORC diagram," *J. Appl. Phys.*, vol. 93, no. 10, pp. 6620–6622, 2003.

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