Invited Paper

Identification procedures for Preisach-type models based on FORC diagrams

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In the paper one presents the relation between the Preisach-type models in which the interaction field distribution is state dependent and the FORC diagram. The method used for the calculation of the FORC diagram is extended to Multiple Order Reversal Curves (MORC) that can cover minor hysteresis loops. The relation between the MORC and FORC diagrams is presented and it is shown that FORC-type method can be used with sufficient accuracy when in the experiment the saturation is not reached.

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1. Introduction

The persistent interest in the development of more reliable and straightforward experimental methods for the evaluation of the magnetic interactions in various systems is motivated both by the wide availability of the equipment necessary for such measurements in many laboratories and by the importance of these effects on the magnetic properties of materials. In this field the most significant recent event was the proposal to use a set of First Order Reversal Curves (FORC) [1], [2]; this method is known as an identification method of the Preisach distribution for systems correctly described by the Classical Preisach Model (CPM systems) [3]. The really original aspect of the “FORC diagram method” is that it extends method’s application area to *any* magnetic system. However, the method maintains strong links with the Preisach model. The FORC distribution is calculated as the second order mixed derivative of the moment measured on the first order reversal curves [1], [2]:

$$\rho\left(H,H_r\right)=-\frac{1}{2}\frac{\partial^2 m_{FORC}^{-}\left(H,H_r\right)}{\partial H\partial H_r} \qquad (1)$$

where H is the applied field during the measurement of one FORC for a given reversal field, noted with H_r. The sample magnetic moment on a FORC that starts on the descending branch of the major hysteresis loop (MHL) was noted with $m_{FORC}^{-}\left(H,H_r\right)$. For CPM systems, the normalized magnetic moment on a FORC is given by:

$$m_{FORC}^{-}\left(H_\alpha,H_\beta\right)=1-2e\left(H_m,H_\beta\right)+2e\left(H_\alpha,H_\beta\right) \qquad (2)$$

where $H\equiv H_\alpha, H_r\equiv H_\beta$ are the Preisach notations, and $e\left(H_\alpha,H_\beta\right)$ is the Everett integral and H_m is the maximum coercivity of the particles in the system. Using the curves calculated with (2) in the definition of the FORC distribution (1) one obtains directly the distribution of the coercive and interaction fields for the particles in the system, that is, the Preisach distribution. One problem is that this is exactly true *only* for CPM systems, that is, for systems obeying to the wiping-out and congruency properties [3]. A number of characteristic features were observed on many experimental FORC diagrams (contour plots of FORC distribution) that are clearly in conflict with the properties of Preisach distributions. As the most significant feature, negative regions were observed on diagrams, fact that initially was considered as an indication that the FORC diagram method is more general than the Preisach model. Nevertheless, studies have shown that most of the observed elements can be reproduced with modified Preisach models, like the Moving Preisach Model (MPM), [2, 4], that take into account the mean field interactions.

The problem we analyze in this paper is related to the state dependence of the interaction field distribution (IFD). Recent micromagnetic calculations made on systems of Stoner-Wohlfarth particles have shown that IFD have a quite strong dependence on the magnetic moment of the sample. IFD is usually characterized by the mean value and the dispersion and both are observed to depend on the magnetic state of the sample [5], [6]. Due to the technological interest in the use of magnetic patterned media as ultra-high density recording media, studies concerning the interactions in these media were also made and they have shown that the state dependence is stronger in such systems [7] and a complex structure of the IFD with more than one peak was also observed [8], [9] which was confirmed by Ising-type models [10].

2. PM2 model. FORC and MORC diagrams

To perform a systematic study of the relation between the FORC distribution and the IFD especially in systems with strong state dependence of interactions, we used a model recently developed by us, [8], [11], named Preisach Model for Patterned Media (PMPM or PM^2), that can include in a straightforward manner Preisach distributions with two peaks, both dependent on the magnetic moment of the sample. As the IFD can be written as a sum of two terms, one independent of the magnetic state $p_{ii,0}$ and one proportional to the magnetic moment of the sample, $p_{ii,m}$, $p_{ii}(h_i) = p_{ii,0}(h_i) + m p_{ii,m}(h_i)$, one obtains a similar representation for the Preisach distribution $p_i(H_\alpha, H_\beta) = p_{i,0}(H_\alpha, H_\beta) + m p_{i,m}(H_\alpha, H_\beta)$ and for the Everett integral (irreversible part) $e_i(H_\alpha, H_\beta) = e_{i,0}(H_\alpha, H_\beta) + m e_{i,m}(H_\alpha, H_\beta)$. The PM^2 model has a major advantage over the Preisach-type models like the moving and variable variance models given by the fact that avoids the iterative processes implied by both mentioned models [11]. For example, in the PM^2 model, the magnetic moment on the descending branch of the Major Hysteresis Loop (MHL), m^-_{MHL}, is given in the explicit form:

$$m^-_{MHL}(H) = \frac{1 - 2e_{i,0}(H_m, H)}{1 + 2e_{i,m}(H_m, H)} \tag{3}$$

(throughout this paper we shall consider that the reversible part is negligible). Similar expressions can be obtained for higher order curves. The FORC starting on the descending branch of the MHL, at the reversal field H_r, is given by:

$$m^-_{FORC}(H) = \frac{1 - 2e_{i,0}(H_m, H_r) + 2e_{i,0}(H, H_r)}{1 + 2e_{i,m}(H_m, H_r) - 2e_{i,m}(H, H_r)}. \tag{4}$$

With the PM^2 model we have generated FORCs and then we have compared the diagram with the known Preisach distribution. The goal of our study is to analyze the capacity of the FORC diagram method to evidence state dependent IFD. As a normal requirement in order to produce *first* order curves, we have to start from a saturated state and to reverse the field on one of the Major Hysteresis Loops' (MHL) branches. However, it is known that the state dependence can be detected experimentally on *minor hysteresis loops* which are containing higher order magnetization curves. As these minor loops can be also covered with magnetization curves (as in the FORC procedure on the MHL) we are analyzing the significance of the distribution that can be calculated with a similar numerical procedure on a minor loop. The FORC-type curves that scan the surface of a minor loop are Multiple Order Reversal Curves (MORC) and correspondingly one obtains MORC distribution and diagram. We shall compare the FORC and MORC diagrams measured in the same field domain which will also offer an evaluation of the errors in the case of FORC-type measurements when the maximum field in the experiment doesn't saturate the sample.

To make that analysis more systematic, we shall start with a case for which the answer can be obtained even analytically, for CPM systems. We know that these systems show the congruency property, that is, the minor hysteresis loops measured between the same field interval should have the same shape. In the PM^2 model, the moment in the state E (see Fig. 1, curve DEC) is given by:

$$m_E(H_{r0}, H_{r1}, H_{r2}, H) = \frac{1 - 2e_{i,0}(H_m, H_{r0}) + 2e_{i,0}(H_{r1}, H_{r0}) - 2e_{i,0}(H_{r1}, H_{r2}) + 2e_{i,0}(H, H_{r2})}{1 + 2e_{i,m}(H_m, H_{r0}) - 2e_{i,m}(H_{r1}, H_{r0}) + 2e_{i,m}(H_{r1}, H_{r2}) - 2e_{i,m}(H, H_{r2})} \tag{5}$$

Using the definition of the Everett integral in (5) and applying the second order mixed derivative, as in (1), one obtains:

$$\rho(H, H_{r2}) = -\frac{1}{2}\frac{\partial^2 m_E(H, H_{r2})}{\partial H \partial H_{r2}} = p_i(H, H_{r2}) \equiv p_i(H_\alpha, H_\beta) \tag{6}$$

where the relation with the standard Preisach notation is: $H \equiv H_\alpha, H_{r2} = H_\beta$. From (6) one concludes that the method will offer a section of the entire FORC diagram (or Preisach distribution). For CPM systems all the congruent minor loops offers the same region of the FORC diagram. In Figs. 2 and 3 one show the result of the FORC (Fig. 2) and MORC diagrams measured for three congruent minor loops (Fig. 3). We have also to emphasis that the section of the FORC diagram is within the method's errors (given mainly by the field step size and the approximation method for the mixed derivative) identical with the FORC diagram obtained with the standard procedure. This offers new perspectives for the method improvement; this show that even if the saturation is not achieved the FORC-type method (in fact a MORC method in this case), offers valuable information about the system. Of course, this is entirely true only for the CPM systems.

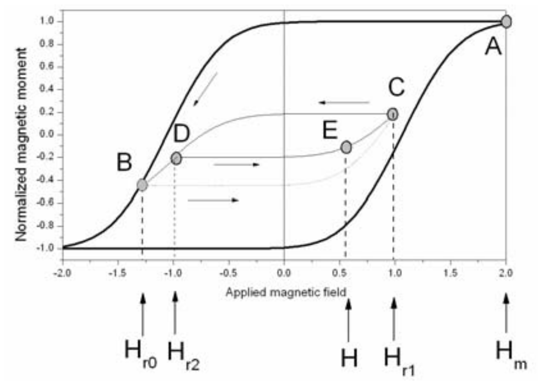


Fig. 1. A minor loop on which systematic MORCs can be measured. To attain the point D the system has to pass through the states: ABCD. The field sequence to obtain the state E is $(H_m, H_{r0}, H_{r1}, H_{r2}, H)$. *Since the state depends only on the local minima and maxima in the history of the applied fields, the moment in E shall depend only on the mentioned fields in the list.*

3. Discussion and conclusions

To evaluate the possible errors for systems with state dependent interactions, we have made simulations with PM^2 model. In Figs. 4 one show the comparison between the region of the FORC diagram that can be compared with the regions obtained with two minor loops (one around the demagnetized state and one at a higher moment, $m \simeq 0.25$). One observes slight differences between the results, which are evidencing the fact that the minor loops are not congruent and the MORCs as well. We know that a limit of the interactions characterization using FORC diagram is the fact that it gives only a static and average image of IFD in contrast with the physical reality which implies more complex state dependent IFD. Using MORC diagrams one can observe the state dependence of the interaction distribution. However, the MORC diagrams have limited value in this matter since they cover only a small region from the entire FORC diagram.

Nevertheless, this study offers a valuable result: the MORC-diagram method is not restricted to experiments in which the sample can be saturated. The MORC diagram describes with a certain degree of accuracy a region of the FORC diagram. If the minor loops are measured between wider field limits, the possible shift of these loops along the moment direction becomes more and more limited. As the interactions depend on the magnetic moment of the sample, if the average moment around which we are measuring the minor loop is not changing significantly, the MORC diagram will be almost identical to the FORC diagram within the same field limits. In Fig. 5 one present the MORC diagram for the same system used in Fig. 2 but the measurement was made not between -2 and 2, as in Fig. 2 but between -1.75 and 1.75. These fields are not sufficient to close the major hysteresis loop (the closure field is around 2.0) but a reasonable agreement between the FORC and MORC diagrams is observed on the region covered by the MORC diagram.

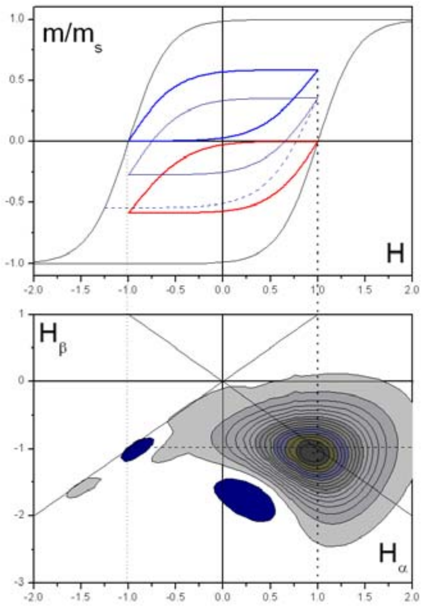


Fig. 2. A sectionn of the FORC diagram was obtained using the MORC diagram for minor loops. All the three minor loops offers the same diagram.

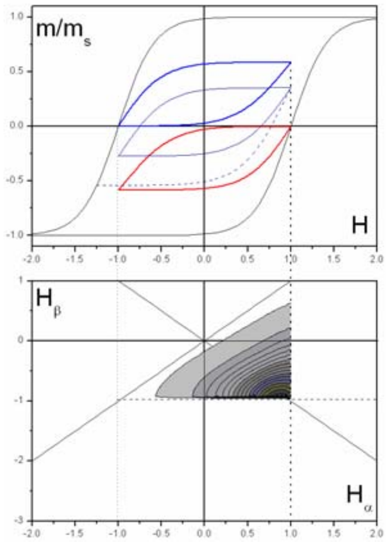
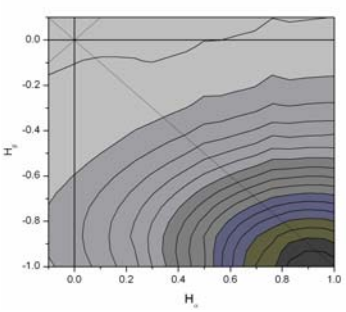
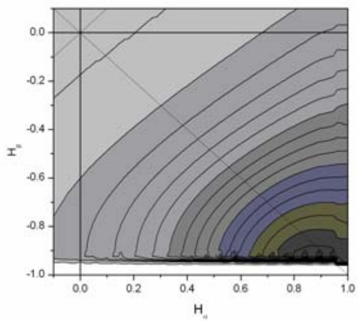


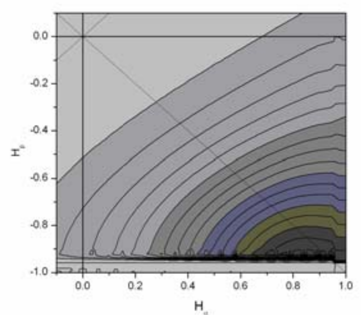
Fig. 3. MORC diagram obtained for curves that cover any of the three minor hysteresis loops.



a) FORC



b) MORC ($\overline{m} = 0$)



c) MORC ($\overline{m} = 0.25$)

Fig. 4. Comparison between the diagram of the region covered by minor loops. a) the FORC diagram of the zone; b) and c) MORC diagrams of the zone for two values of the moment in the minor loop.

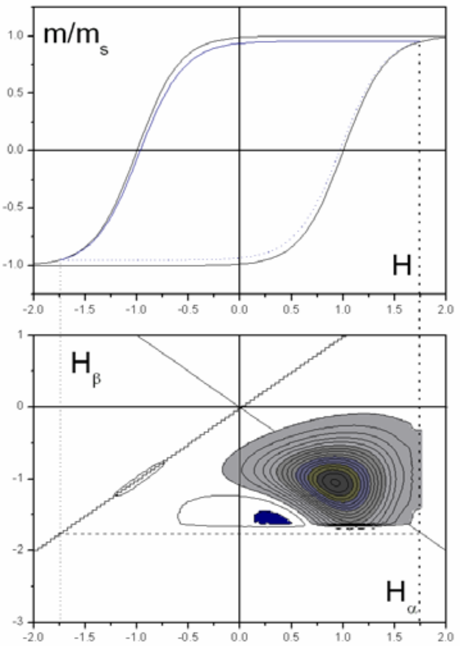


Fig. 5. MORC diagram for a minor loop very close to the MHL.

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References

[1] C. R. Pike, A. P. Roberts, K. L. Verosub, J. Appl. Phys. **85**(9), 6660 (1999).
[2] A. Stancu, C. R. Pike, L. Stoleriu, P. Postolache, D. Cimpoesu, J. Appl. Phys. **93**(10), 6620 (2003.
[3] I. D. Mayergoyz, Mathematical Models of Hysteresis (Springer, New York, 1986).
[4] E. Della Torre, IEEE Trans. Audio Electroacoust., **AE-14**, 86 (1966).
[5] A. Stancu, L. Stoleriu, M. Cerchez, J. Magn. Magn. Mater. **225**(3), 411 (2001).
[6] F. J. Morentin, O. Alejos, J. Munoz, L. Torres, L. Lopez-Diaz, J. Appl. Phys. **93**(10), 6641 (2003).
[7] D. Cimpoesu, P. Postolache, A. Stancu, J. Appl. Phys. **93**(10), 6644 (2003).
[8] A. Stancu, L. Stoleriu, P. Postolache, M. Cerchez, IEEE Trans. Magn. **40**(4), 2113 (2004).
[9] M. Cerchez, L. Stoleriu, A. Stancu, J. Optoelectron. Adv. Mater. **5**(4), 933 (2003).
[10] R. Tanasa, C. Enachescu, A. Stancu, J. Linares, F. Varret, J. Appl. Phys. **95**(11), 6750 (2004).
[11] A. Stancu, L. Stoleriu, P. Postolache, R. Tanasa, J. Magn. Magn. Mater. **290-291,** 490 (2005).

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