Preisach model for systems with asymmetric First order reversal curve (FORC) distribution

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This paper addresses the problem of asymmetry of the First-order Reversal Curve (FORC) diagram in correlation with the symmetry of the Preisach distribution. Only in a few cases, for the exchange-bias materials for example, an asymmetric distribution in the demagnetized state has to be considered in the Preisach model. In relation to the case of exchange bias materials a correlation between the distribution of interactions and that of the coercivities was considered. The FORCs starting on the ascending and descendent branches of the major loop are calculated with a Moving Preisach Model. The results show a good resemblance with typical experimental results on exchange bias materials.

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1. Introduction

The first order reversal curve (FORC) method initially designed as an identification technique for the Classical Preisach Model (CPM) [1] is now in many laboratories used as a general experimental procedure which gives a diagram describing essentially the distribution of coercivities and interaction fields for a system [2, 3]. However, even if initially the method was seen as a more general approach than the Preisach model, the FORC diagram method and the results obtained with it can be understood within the Preisach paradigm. A fundamental feature which can be observed on most experimental FORC diagrams is that they are essentially asymmetric. This could appear strange due to the fact that the hysteresis loop and even the FORCs usually show a high degree of symmetry. As a natural consequence, it is of paramount importance to understand correctly this attribute in order to properly make use of the experimental FORC diagram results. In this paper we shall make this analysis with the help of a number of Preisach models.

2. FORC distribution and the classical Preisach model

The fundamental brick of the Classical Preisach Model is the elementary rectangular hysteresis loop, which is usually called hysteron or Preisach hysteron or even rectangular hysteron. From the physical point of view, this could be associated in our mind with the hysteresis loop of a uniaxial single domain particle when the field is applied along the easy axis. However, the Preisach system is not a simple superposition of Stoner-Wohlfarth hysterons which, regardless of their anisotropy, have a symmetry [2, 3] with respect to the (H,m) coordinate system, where H is the applied field and m is the magnetic moment. The main ingredient of the CPM is the distribution of interaction fields in the system, which has the effect of shifting the rectangular hysteresis loop with a value equal to the interaction field. Therefore, the classical Preisach system is a distribution of symmetric and asymmetric hysterons. Each sample will be represented by such a distribution, called *Preisach distribution* and, consequently, the main problem of the model is to find this distribution from experimental data.

Mayergoyz [1] has designed an elegant experimental procedure, based on the measurement of a set of first-order reversal curves, which allows acquiring the Preisach distribution for a CPM system (a system which obeys to the congruency and wiping-out properties [1]). As most of the real systems are not CPM systems, the FORC-based identification method will fail. However, Pike and co-workers have proposed that the identification method should be used for any system as a purely experimental procedure [4]. The FORC method is using a set of typically 100 first-order reversal curves starting on the descendent or the ascendant branches of the Major Hysteresis Loop (MHL). The magnetic moment on a FORC is a function of two variables: the applied field, H, and the reversal field at the starting point on the FORC, H_r, that is, $m^{\pm}_{FORC}(H,H_r)$, where the "$+$" if for the FORCs starting on the ascending branch of MHL and "$-$" is for ones starting on the descendent branch of MHL. The FORC distribution, noted with $\rho(H,H_r)$, is given by the second order mixed derivative of the moment measured on the FORC:

$$\rho(H,H_r) = \pm\frac{1}{2}\frac{\partial^2\left[m^{\pm}_{FORC}(H,H_r)\right]}{\partial H\partial H_r} \qquad (1)$$

where the factor $(1/2)$ is assuring that for the CPM systems the FORC distribution is identical to the Preisach distribution regardless on the use of ascendant or descendent branches of MHL. With the standard Preisach notation, $H = H_\alpha$ is the superior switching field of the hysteron and $H_r = H_\beta$ is the inferior switching field of the hysteron and the Preisach distribution, $P(H_\alpha, H_\beta)$ is identical to the FORC distribution $\rho(H, H_r)$ for CPM systems.

3. Symmetry of magnetization curves and the FORC diagrams

In most of the classical magnetic materials one expects to measure a major loop which is symmetrical with respect to the origin of the coordinate system (H, m).

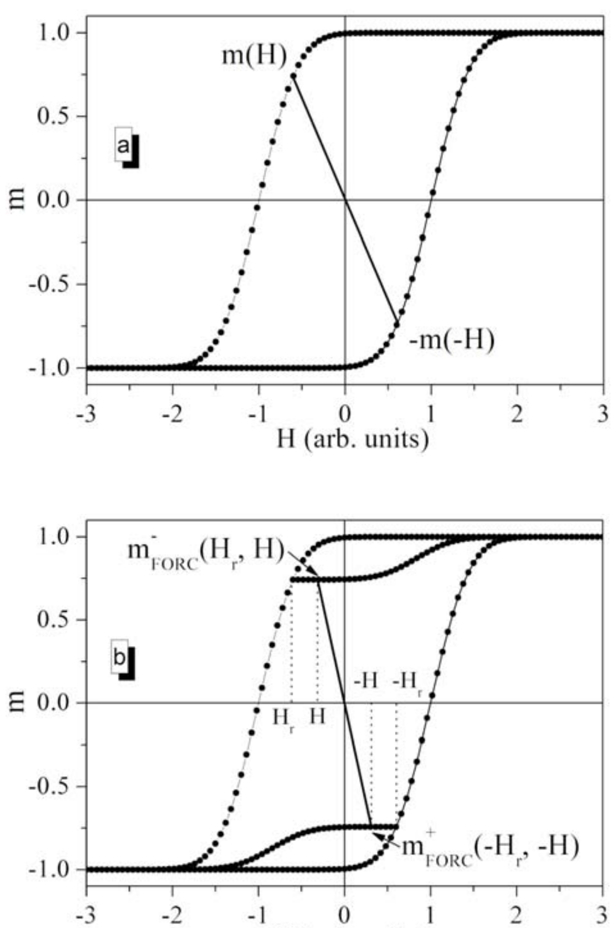

Fig. 1. (a) - symmetrical branches of the major hysteresis loop and (b) - symmetrical first-order reversal curves.

Also the first-order reversal curves from the descendent branch of the major loop are usually symmetrical with the corresponding first-order curve starting on the ascending branch of the MHL (see Fig. 1).

The symmetry of the major loop is usually taken as motivation for a symmetric Preisach distribution in the classical Preisach model with respect to the second bisector of the Preisach plane, that is the axis of zero interaction field. We have to emphasize that both the symmetry of the major loop and of ascending and descending FORCs are only compatible in CPM with a symmetric Preisach distribution. Any asymmetry of the Preisach distribution will induce an asymmetric major loop. However, the FORC procedures will produce regardless on the branch they are measured the same FORC distribution, identical to the Preisach distribution for CPM systems.

When the FORC experiment is performed on non-CPM systems, the most frequent case is when the major loop and the FORCs show the symmetry mentioned previously but the FORC distribution (and the FORC diagram which is the contour map of the FORC distribution) is not symmetric with respect to the “no-interactions” axis (see Fig. 2). However, the ascending and descending FORC distributions are symmetrical to each-other. A simple explanation can be given to this case if we consider a mean field interaction field in the Classical Preisach Model. One obtains the well-known Moving Preisach model [6] which can reproduce easily such a case. This asymmetry can be used to evaluate the intensity of the mean field term (the moving parameter) [7] and statistical procedures can be implemented [8] to evaluate quantitatively the asymmetry of the experimental FORC diagram.

This procedure proved to be extremely efficient in the case of patterned media [8, 9]. More sophisticated Preisach models, like the Variable Variance model [10], or PM2 [11, 12] can also reproduce this case with a fundamental distribution of interaction fields which becomes asymmetric as a function of the system output (the magnetic moment of the sample). For a limited number of materials however, the two FORC diagrams that can be measured from the same hysteresis loop, using either the ascending or the descending branch, are not symmetric between them (measurements made on exchange bias materials [13]). This case can’t be reproduced by the Moving model if the Preisach distribution in the demagnetized state (unaffected by the mean field) is symmetric. The other models mentioned before are also failing to address this problem. In this case we have to use asymmetric Preisach distributions even in the demagnetized state.

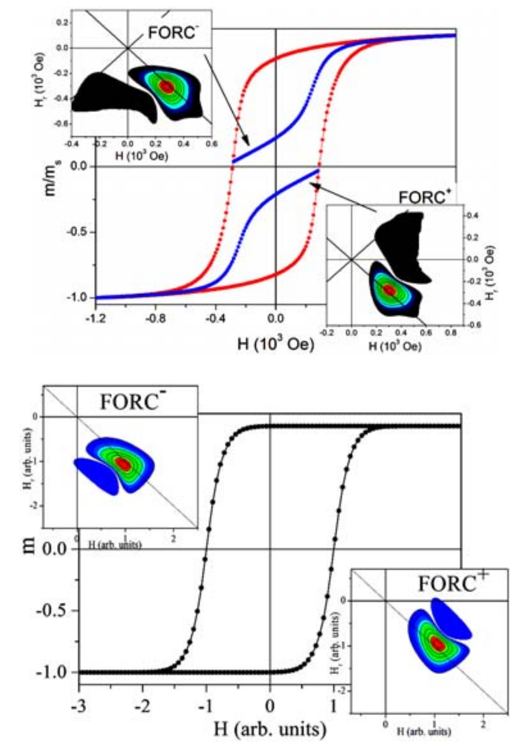

Fig. 2. FORC diagrams measured for a standard magnetic tape (top); simulated FORC diagrams using a Moving Preisach Model (bottom). The diagrams are asymmetrical with respect to the $H_1 = 0$ axis but FORC$^-$ and FORC$^+$ are symmetrical with each other.

4. Preisach model with asymmetric Preisach distribution

In order to propose an asymmetric Preisach distribution for the mentioned systems we started from the observation that the FORC distribution measured on the descending branch on the major loop show in many cases a tail which at higher fields becomes almost parallel to the reversal field axis (or the down switching field in Preisach terminology) [14] (Fig. 3). Similar diagrams are obtained in ferroelectric systems [15]. This kind of behavior suggests that the shift of the hysteron (the exchange field) is higher for higher coercivities. To take that into account we have considered the following Preisach distribution:

$$f\left(h_i, h_c\right) = \frac{1}{2\pi\sigma_{h_i}\dfrac{\sigma_{h_c}}{h_c^0}} \cdot \frac{1}{h_c} \cdot \exp\left(-\left(\left(\frac{h_i - h_{i0}}{2\sigma_{h_i}}\right)^2 + \frac{\ln^2\left(\dfrac{h_c}{h_c^0}\right)}{2\left(\dfrac{\sigma_{h_c}}{h_c^0}\right)^2}\right)\right) \quad (2)$$

with $h_{i0} = C\left(h_c\right)^{\gamma} + h_s$, where C and γ are the parameters controlling the correlation degree and h_s is the shift of the interaction distribution. The coercitivities are distributed lognormal with average h_c^0 and standard deviation σ_{h_c} while the interactions follow a Gaussian-type distribution with the average h_{i0} and standard deviation σ_{h_i}.

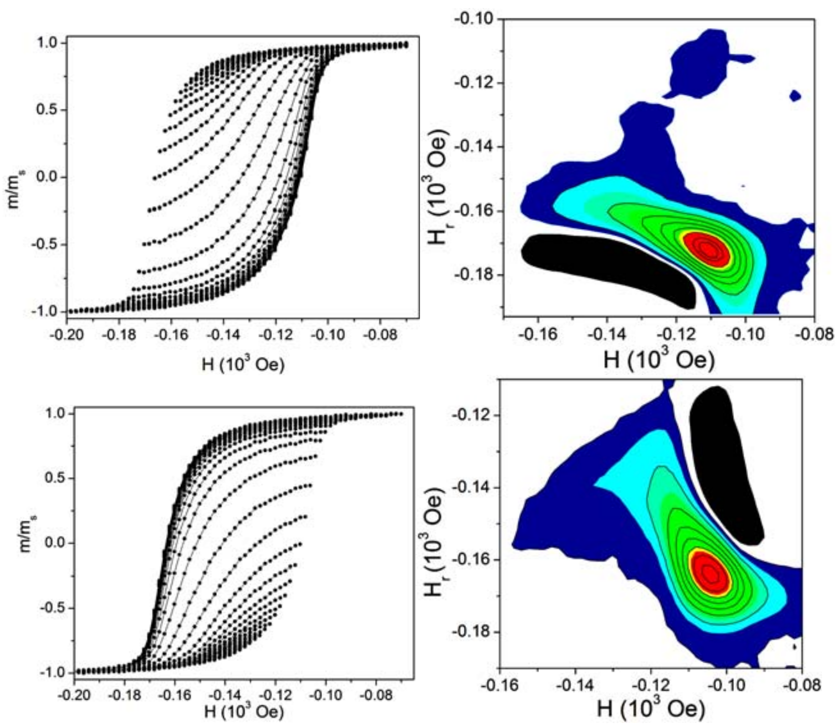

Fig. 3. FORCs and FORC diagram of IrMn10-Co5 exchange bias bilayer measured on both branches of MHL.

If we use a classical Preisach model with this distribution, we obtain from both FORC diagrams (ascending and descending) the same asymmetric distribution. However, when we use the mean field term the FORC distributions become different and they did not show any type of symmetry between them. What is really remarkable is that the mean field term could have such an effect on the asymmetric Preisach distribution that on the ascending branch FORC distribution the correlation we took into account between the exchange field and coercivity is much less visible, which was observed on some exchange bias thin film samples (Fig. 4).

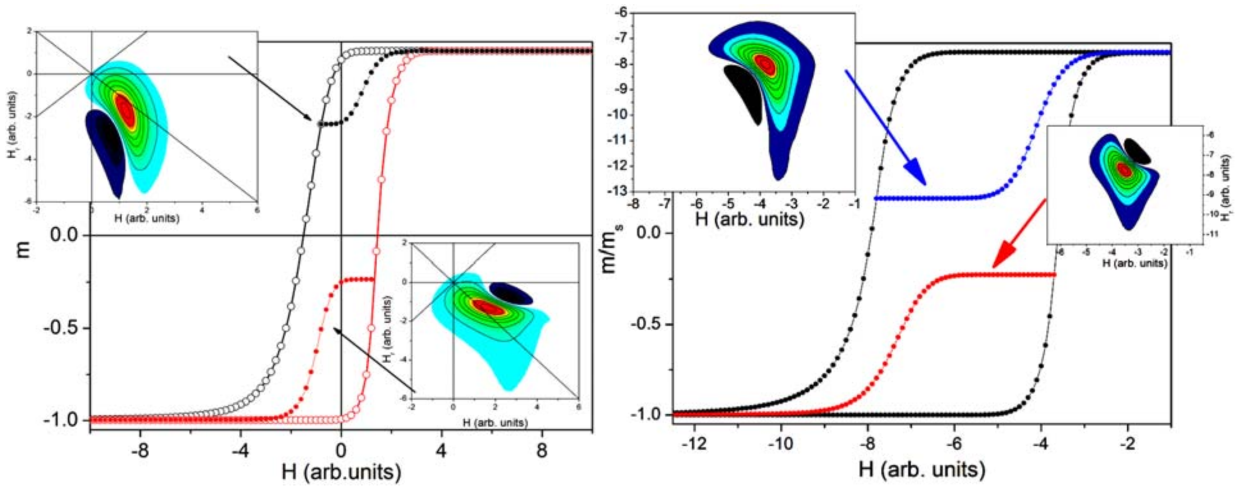

Fig. 4. FORC distributions obtained from a moving Preisach model which uses the asymmetrical distribution from Eq. 2 with $h_s = 0$ *(top) and* $h_s = -8$ *(bottom).*

5. Conclusions

The symmetry of the experimental FORC distribution/diagram contains essential information about the magnetic system measured. An asymmetry of the FORC diagram correlated with a symmetric major loop is the indication of a state dependent interaction field distribution. A mean field term with a symmetric Preisach distribution could reproduce easily this type of diagrams. However, this model (moving Preisach) when applied to simulate both ascending and descending FORCs, produces diagrams which are symmetric to each other. When the experimental ascending and descending FORC distributions are not symmetric between them, like in the case of exchange bias materials, a non-symmetric Preisach distribution has to be considered. This result shows that the asymmetric major loop is not necessarily caused by different type of magnetization processes, as it has been attributed in some exchange biased systems.

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