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Comparison of identification protocols of a static hysteresis model

Maria-Roberta Longhitano¹ Fabien Sixdenier², Riccardo Scorretti^{1,2},
Christophe Geuzaine³, François Henrotte³, Laurent Krähenbühl¹

¹Univ Lyon, ECLyon, Université Claude Bernard Lyon 1, INSA Lyon, CNRS, Ampère, F-69130, Ecully, France

²Univ Lyon, Université Claude Bernard Lyon 1, INSA Lyon, ECLyon, CNRS, Ampère, F-69100, Villeurbanne, France

³Institute Montefiore - ACE - Université de Liège, B-4000 Liège, Belgium

In order to predict magnetic quantities in the magnetic cores of electrical devices, scientists and engineers need hysteresis models sufficiently accurate. Whatever the chosen model is, a dedicated identification protocol has to be elaborated requiring more or less specific measurements. This article compares, at least, two identification protocols of the same hysteresis model parameters. The protocols themselves, their inputs and outputs and their accuracy are detailed and discussed.

Index Terms—Magnetic cores, Magnetic devices, Magnetic hysteresis, Magnetic materials, . . .

I. INTRODUCTION

HYSTERESIS models are necessary to predict magnetic quantities in electrical devices for simulation or design purposes. The most used models are the Jiles Atherton (JA) model [1] and the Preisach model (PM) [2]. One of the last developed model which has a lot of desirable properties is a vector play model (VPM) firstly introduced by Berqvist [3] such as being intrinsically vectorial. Then, pursuing the work, Henrotte showed that its "energy based model" (EBM) provides an accurate energy balance [4] and that the number of cells can strongly improve the accuracy [5]. However, the identification of the model parameters and the number of necessary cells were still issues. That's why two identification protocols concerning this model were proposed in [6] and [7]. The first one is based on an optimization problem where some constraints have been relaxed and a packing algorithm has been proposed. Several objective functions have been tested and gave similar results in terms of accuracy. Moreover this method gave satisfactory results when the temperature has been taken into account. The second one is based on a specific measurement set and the construction of a mathematical function which has to be derived twice in order to obtain the final parameters distribution. In addition, this method gave some qualitative information about the material microstructure (average grain size, density of defects, . . .) We propose, in this article, to compare these two methods. The paper is organized as follows. The next section will describe, the model and the both identification methods principles. The third section will present the investigated soft magnetic material followed by the measured and simulated results with both methods. Last section is the conclusion.

II. MODEL AND IDENTIFICATION METHODS

A. hysteresis model

The VPM separates the excitation field \mathbf{h} into a reversible \mathbf{h}_{re} and an irreversible part \mathbf{h}_{ir} (1)

$$\mathbf{h} = \mathbf{h}_{re} + \mathbf{h}_{ir} \quad (1)$$

To obtain a better accuracy, the model is subdivided into cells. Thus \mathbf{h}_{re} is a weighted sum of \mathbf{h}_{re}^k contributions of a certain number of cells N (2).

$$\mathbf{h}_{re} = \sum_{k=1}^N \omega_k \mathbf{h}_{re}^k \quad (2)$$

In (2), $\omega_k \geq 0$ is the weight associated with the k cell and must verify $\sum_{k=1}^N \omega_k = 1$. The term \mathbf{h}_{re}^k is the internal state of the cell k . It is updated such as (3)

$$\mathbf{h}_{re}^k = \begin{cases} \mathbf{h}_{re0}^k & \text{if } \|\mathbf{h} - \mathbf{h}_{re0}^k\| < \chi^k \\ \mathbf{h} - \chi^k \cdot \frac{\mathbf{h} - \mathbf{h}_{re0}^k}{\|\mathbf{h} - \mathbf{h}_{re0}^k\|} & \text{otherwise} \end{cases} \quad (3)$$

where χ^k is the corresponding maximum pinning field of the k cell. The magnetization \mathbf{M} is calculated from \mathbf{h}_{re} (4).

$$\mathbf{M} = M_{an}(\|\mathbf{h}_{re}\|) \cdot \frac{\mathbf{h}_{re}}{\|\mathbf{h}_{re}\|} \quad (4)$$

Where $M_{an}(\|\mathbf{h}_{re}\|)$ is a scalar anhysteretic function. Finally the flux density \mathbf{b} is obtained with (5)

$$\mathbf{b} = \mu_0(\mathbf{M} + \mathbf{h}) \quad (5)$$

The parameters to identify are then (ω_k, χ^k) . Note that, the (ω, χ) distribution can be identified from unidirectional measurements. That's why the vector notations will no longer be present in the document.

B. Identification by optimisation [6]

The naive way to identify the (ω_k, χ^k) sets could be such as (6), where the the vectors $Y = (\omega_1 \dots \omega_N)$ and $X = (\chi^1 \dots \chi^N)$.

$$\begin{cases} (\omega_k, \chi^k) = \arg \min_{Y, X} \|b(h) - b_s(h)\|_2^2 \\ \omega_k \geq 0 ; \sum_{k=1}^N \omega_k = 1 \\ \chi^1 = 0 ; \chi^k \leq \chi^{k+1} \end{cases} \quad (6)$$

It is proposed to solve (7) instead for reasons detailed after.

$$\begin{cases} \Delta\chi^k = \arg \min_{\Delta X} \|b(h) - b_s(h)\|_2^2 \\ \omega_k \equiv 1/N \\ \Delta\chi^k \geq 0 \end{cases} \quad (7)$$

Where $\Delta X = (\Delta\chi^1 \dots \Delta\chi^{N-1})$ and $\Delta\chi^k = \chi^{k+1} - \chi^k$. With the formulation (7) the problem is "only" a non-negative least square problem. Moreover, (7) has a reduced number of unknowns than (6) ($N-1$ compared to $2N-1$). The major improvement is that ω_k is imposed and is no longer a degree of freedom. It is then much easier to solve and avoid of local minima. The price to pay is that a higher number of cells is in principle necessary to obtain a comparable accuracy. That's why, the identification protocol is actually made in two steps. The first step is to solve (7) with a "high" number of cells and then reduce it thanks to a packing cells algorithm shortly described hereafter (more details in [6]).

C. Identification protocol based on $h_c(h_p)$ curve [7]

In [7], it is mandatory to have the $h_c(h_p)$ curve (h_p is the peak value of an alternating excitation field and h_c is the corresponding coercive field) as input data. This measured curve has first to be interpolated and extrapolated as (8). Where $h_{p_{threshold}}$ is the peak value where h_c saturates to its maximum value $h_{c_{max}}$ when h_p goes beyond.

$$h_c(h_p) = \begin{cases} h_c = h_{c_{max}} & \text{if } h_p > h_{p_{threshold}} \\ h_c = \text{interpolation} & \text{if } h_{p_{min}} < h_p < h_{p_{max}} \\ h_c = h_{c_{min}} \cdot \left(\frac{h_p}{h_{p_{min}}}\right)^2 & \text{if } h_p < h_{p_{min}} \end{cases} \quad (8)$$

Then the auxiliary function $F(h)$ is built: a first point is chosen such as $h > h_{c_{max}}$ which gives $F(h) = h - h_{c_{max}}$. The next points are constructed recursively (9) (10)

$$h^n = \frac{h^{n-1} + h_c(h^{n-1})}{2} \quad (9)$$

$$F(h^n) = \begin{cases} h^n - h_{c_{max}} & \text{if } h^n > h_{p_{seuil}} \\ \frac{F(h^{n-1})}{2} & \text{otherwise} \end{cases} \quad (10)$$

Then $F(h)$ is numerically derived twice (11) which gives a quite continuous $\omega(h)$ distribution. After that, several ω_k and χ^k sets are chosen so as to represent quite accurately the continuous $\omega(h)$ distribution.

$$\partial_h F = \int_0^h \omega(\chi) d\chi ; \partial_h^2 F = \omega(h), \quad (11)$$

III. RESULTS

In order to avoid any measurement problem, we tested the methods with a virtual material. The virtual material has a Langevin $M_{an}(h)$ function such as (12), with $M_s = 1e6$ A/m the saturation magnetization and $h_0 = 10$ A/m a shape coefficient. The ω_k and χ^k values for the virtual material and those identified by both methods are given in the table I.

$$M_{an}(h) = M_s \left[\coth\left(\frac{h}{h_0}\right) - \frac{h_0}{h} \right] \quad (12)$$

TABLE I
REFERENCE AND IDENTIFIED VALUES OF ω_k AND χ^k SETS

Reference	ω_k	0.1	0.4	0.3	0.2
	χ^k	0	1	5	15
[6]	ω_k	0.1667	0.333	0.3333	0.1667
	χ^k	0	0.9865	4.8809	11.45
[7]	ω_k	0.22	0.521	0.226	0.04
	χ^k	0	3.17	13.83	63.32

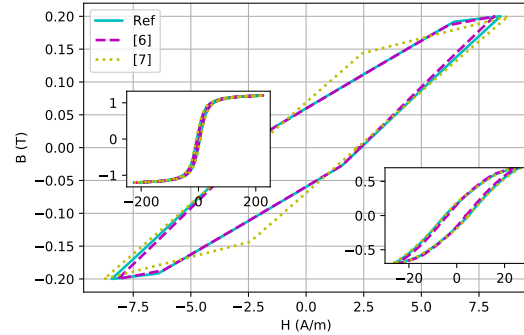


Fig. 1. Loops at different amplitudes. Reference loop (solid line), loops simulated with parameters identified by [6] (dashed line) and loops simulated with parameters identified by [7] (dotted line)

Results show that both methods failed to retrieve "exactly" the parameters sets. The method [6], retrieved quite well the χ^k values (exception for the last value), but the weights are relatively different. The method [7] failed to retrieve both χ^k and ω_k . Thus a better accuracy is achieved for loops simulated with parameters identified by [6] than with [7], especially for low amplitude loops.

IV. CONCLUSION

The extended paper will present more details about the identification methods, more results with real materials and further discussion about accuracy and robustness of each method.

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