A new and robust hysteresis modeling based on simple equations

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In this paper we propose a new approach for modeling scalar hysteresis based on simple equations. The proposed technique is based on simple equations and its treatment is more direct than the well-known Preisach and Jiles-Atherton models. As main basis, the shape of the external hysteresis curves is strongly considered, allowing a correct behavior of magnetic induction evolution inside the hysteresis cycle.

***Index Terms*—magnetic hysteresis, hysteresis model, curve fitting.**

I. INTRODUCTION

WE ARE using, with good results, the classical and well known Jiles-Atherton hysteresis model for several years [1,2,3]. In collaboration with another research group, Preisach model have been also employed on our simulations [4]. In spite of their efficiency, such models are complex and somewhat difficult to implement. Even the full understanding and variation sensibility related to their parameters is not trivial. The main purpose of this work is to find a new hysteresis approach based on simple equations. For doing so, as for any related method, it is necessary to have some experimental data from the material to be modeled. In the proposed methodology, only an external hysteresis loop, i.e. the loop reaching the saturation, is necessary. Once such curves are available, we build our model. It is important to note that inner loops as well as the magnetic transitory evolution can be represented using only the external loop information.

II. THE EXTERNAL HYSTERESIS CURVE: TWO POSSIBILITIES

With the $B(H)$ curve obtained by experimental means, it is possible to define the ascendant and descendent external curves by different approaches. Let us consider the Fig. 1.

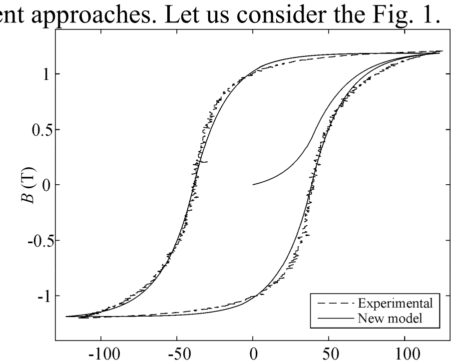

Fig 1 – The hysteresis curve: experimental data and curve of the proposed model.

The observation of the experimental data indicates that the $B(H)$ curve can be represented by different methods. Firstly, it is possible to remark that this curve possesses, with reasonable accuracy, the shape of a dislocated exponential curve. For instance, considering the experimental data of Fig. 1, the $B(H)$ form of Fig.2(a) is approached by the equation $f(h) = B_s\left(1 - e^{-ah}\right)$. B_s and a are found by exponential fitting.

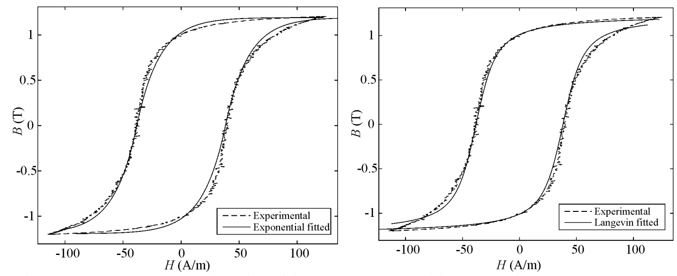

Fig. 2: (a) $B(H)$ curve simulated by an exponential curve. (b) $B(H)$ curve simulated by a sum of two Langevin curves.

The agreement is quite good. A second method has its basis on a dislocated Langevin curve. For the same Fig.1, the Langevin approach is shown in Fig. 2(b); it is given by the formula $B(h) = M_s\left[\coth\left(\frac{h}{a_l}\right) - \frac{a_l}{h}\right]$. As above, the agreement is satisfactory. The use of a Langevin function implies on finding the parameters M_s and a_l.

III. THE B EVOLUTION INSIDE DE B (H) CURVE

The establishment of the external curves, shown above, is the first step for the most challenging task of this work, which is the B evolution inside the cycle. Notice that, if the above techniques fail, it is possible to use a set of $B(H)$ points describing, in a better way, the experimental external curve. Now let us analyze the evolution of the magnetic state for inner loops.

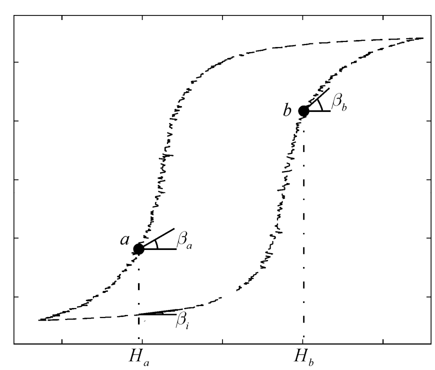

Fig. 3: Evolution of B as function of H with $B(H)$ curve angles.

We consider that a small increment of H must be applied, when the magnetic state is at point a in Fig. 3. It is necessary to find the corresponding angle inside the cycle. Analyzing Fig.3 it can be observed that, at the point H_a (in the descendent branch), angle β_a is related with the angle β_i (H_a in the ascendant branch) and normally smaller than it. Therefore, we choose a factor p_a as $\beta_a = p_a \beta_i$. For instance, p_a can be choose empirically as 0.3. At the other extremity, at H_b, the same phenomenon occurs but the angle β_b is very close to β_i (the *B*(*H*) curve angle). In this case, p_b is defined at the point H_b and, for instance, p_b can be here 0.8. In other words, the evolution of *B*, as function of *H*, goes from a "small" angle at H_a to a situation when the internal curve becomes "tangent" to the ascendant *B*(*H*) hysteresis curve. From this point on, the *H* and *B* increasing follows the external curve. Obviously, when we have the descendent *H*, similar situation occurs. In Fig. 4a the *B* behavior is shown as described above.

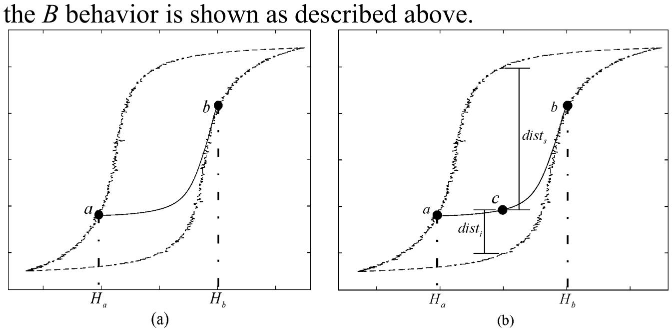

Fig. 4: (a) *B* evolution with $p_a = 0.3$ and $p_b = 0.8$. (b) the evolution of *B* considering the angles and normalized distances.

There is now a crucial point - even though quite simple - on the proposed method: p varies from p_a to p_b. For the sake of explanation, an ascendant internal curve is considered. In Fig.4b a generic point *c* inside the cycle is located between the two points *a* and *b*.

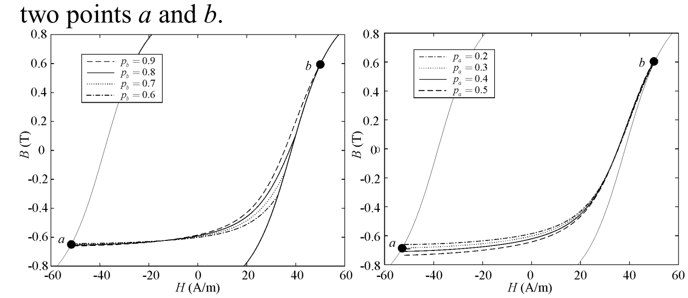

Fig. 5: (a) $p_a = 0.2$ with different p_b. (b) $p_b = 0.9$ with different p_a.

Using the external curves, $dist_s$ and $dist_i$ can be easily calculated. We proceed with the calculation of the normalized d_i and d_s as $d_i = dist_i / (dist_i + dist_s)$ and $d_s = dist_s / (dist_i + dist_s)$. At the point a, $d_i = 1$ and $d_s = 0$; at the point b, $d_i = 0$ and $d_s = 1$. With such definitions, it is possible establish the variation of p going from p_a at $d_i = 1$ to p_b at the point b. It can be easily described by the linear function $p = (p_b - p_a) d_i + p_a$ (other functions could be considered). As an example, we show in Fig. 5 how, from a generic point a, *B(H)* behaviors when p_a and p_b varies accordingly to the figure captions.

Another result is presented on Fig. 6. It shows internal loops when starting at the point $H = 0$ and $B = 0$. H varies periodically, increasing slowly its magnitude.

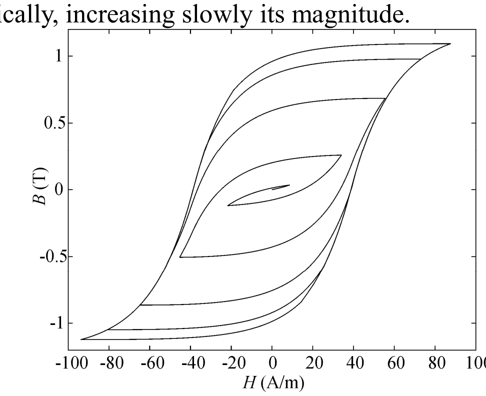

Fig. 6: *B*(*H*) cycles with increasing values of *H* with $p_a = 0.3$ and $p_b = 0.8$.

A comparison with experimental results is presented in the Fig. 7 when *H* varies in a non 'symmetric' way inside the cycle. In this case, the agreement between results from our method and experimental ones is quite good. For this result, we choose $p_a = 0.3$ and $p_b = 0.8$.

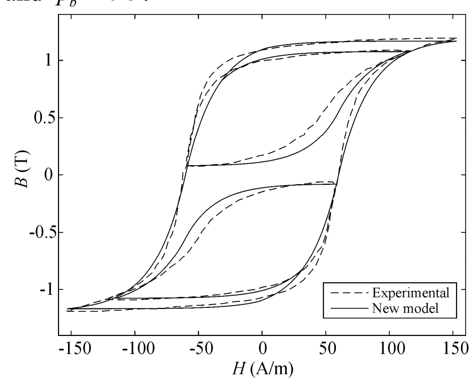

Fig. 7: comparison between results obtained with proposed method and experimental ones.

The main point here is the fact that, just choosing these two parameters (p_a, p_b), the *B*(*H*) behavior can be fairly described, once just one external *B*(*H*) curve is available.

IV. Conclusions

We presented in this paper a new method for modeling the hysteretic behavior of ferromagnetic material. It is based on simple procedures and equations. As shown, it can describe with good accuracy *B*(*H*) curves and it is related to few parameters. They have easy understanding and therefore are simple to handle. At this moment, we are working on improving the method and on the appropriate representation of minor loops. It will be described on the full paper.

References

[1] Bastos, João Pedro Assumpcão and Sadowski, Nelson. *Magnetic Materials and 3D Finite Element Modeling*. New York, NY: CRC Press, 2013.

[2] J. V. Leite, N. Sadowski, P. Kuo-Peng, N. J. Batistela, J. P. A. Bastos and A. A. de Espindola, "Inverse Jiles-Atherton vector hysteresis model," in IEEE Transactions on Magnetics, vol. 40, no. 4, pp. 1769-1775, July 2004.

[3] J. P. A. Bastos et al., "A Differential Permeability 3-D Formulation for Anisotropic Vector Hysteresis Analysis," in IEEE Transactions on Magnetics, vol. 50, no. 2, pp. 341-344, Feb. 2014.

[4] Benabou, A., Clénet, S., and Piriou, F., "Comparison of Preisach and Jiles-Atherton models to take into account hysteresis phenomenon for finite element analysis, "J. Magn. Mater., 261, 139-160, 2003.