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An efficient vector Preisach hysteresis model based on a novel rotational operator

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The vectorial modeling of hysteresis phenomena is an important task with respect to precise numerical simulation of ferromagnetic materials. Many vector models are based on extended Preisach models. Approaches are known where the scalar Preisach models are defined in different space directions and the results are calculated by summation or integration. Within this approach, we suggest a Preisach model that uses only one Preisach plane, but an additional rotational plane. This rotational plane practically defines a direction for each Preisach element. Therefore, this operator can be evaluated in a very efficient way. © 2012 American Institute of Physics. [doi:10.1063/1.3672069]

I. INTRODUCTION

It is well known that vector hysteresis models are necessary to precisely simulate ferromagnetic materials in rotating magnetic fields. Therefore, much effort has recently been put into the development of numerically efficient models. Well-established is the extension of Preisach models with vector methods. Thus, many publications deal with the Mayergoyz vector hysteresis model.¹⁻⁴ Another approach is the Stoner-Wohlfarth model. It has been combined by Kahler with the Preisach model.⁵ A very efficient model has been presented by Adly.⁶ He utilizes coupled step functions in combination with the scalar Preisach approach.

In our approach, we propose a novel rotational operator. A rotation plane is defined, similar to the plane of the switching operators. The plane contains space angles that can be interpreted as the directions in which the switching operators point. In the Preisach integral, this rotation plane is multiplied to the product of the switching operators and the Preisach weights. We define rotation rules similar to the known switching rules. For the Preisach plane, we utilize the derivative-arc-tangent (DAT) function presented earlier.⁷ We demonstrate that the model can be evaluated in a very efficient way even for highly discretized Preisach planes. Therefore, real materials are simulated in a very precise way. The model is validated with vector vibrating sample magnetometer (VVSM) measurements. We show measurements and simulations of sputtered thin films of NiFe and FeCo. Those thin films are used as magnetic core and actuator materials in a micro actuator.⁸

II. MATHEMATICAL FORMULATION OF THE PROPOSED MODEL

A mathematical operator describing scalar hysteretic behavior is the Preisach operator.^{9,10} The general formulation for the continuous Preisach hysteresis operator $\Gamma[\circ]$ is

$$f(t) = \Gamma[u](t) = \int \int_{\alpha \geq \beta} \mu(\alpha, \beta) \gamma_{\alpha\beta}[u](t) d\alpha d\beta, \quad (1)$$

where the time signals $u(t)$ and $f(t)$ denote the input and output, respectively. The weight function $\mu(\alpha, \beta)$ exclusively defines the shape of the hysteresis curve. The parameters of the weight function and the reversible part of magnetization is extensively discussed in Ref. 7. The so-called **switching operators** $\gamma_{\alpha\beta}[\circ]$ can only take the discrete values -1 and 1 . They represent the memory of the scalar hysteresis operator. In Fig. 1 their switching behavior for a certain input value $u(t)$ is illustrated (in the region "older value" no changes occur). The integral is evaluated over the two-dimensional, triangular-shaped Preisach plane.⁹

Here, we present the recently developed efficient vectorial Preisach model $\vec{\Gamma}[\circ]$

$$\vec{v}(t) = \vec{\Gamma}[\vec{u}](t) = \int \int_{\alpha \geq \beta} \mu(\alpha, \beta) \cdot \gamma_{\alpha\beta}[\vec{u}](t) \cdot \vec{\chi}_{\alpha\beta}[\vec{u}](t) d\alpha d\beta. \quad (2)$$

Now, $\vec{u}(t)$ and $\vec{v}(t)$ are the input and output signals as vectorial variation in time. The domain of definition is also restricted to $\|\vec{u}(t)\| \in [-0; 0.5]$. The weight function $\mu(\alpha, \beta)$ still characterizes the shape of the hysteresis curve. The classical scalar operator $\gamma_{\alpha\beta}[\circ]$ is still called **switching operator**. Additionally, a vectorial operator $\vec{\chi}_{\alpha\beta}$ is defined, in the following denoted as **rotational operator**. As operational states of $\vec{\chi}[\circ]$, the unity vectors in $\mathbb{R}^2$ or $\mathbb{R}^3$ are defined, therefore $\|\vec{\chi}_{\alpha\beta}[\circ]\| = 1$. A further distinction between two and three-dimensional modeling is not necessary in this algorithm.

The integral in Eq. (2) is not to be understood as a vectorial surface integral. With $\vec{v} = (v_i)$ and $\vec{\chi}_{\alpha\beta}[\circ] = (\chi_{\alpha\beta,i}[\circ])$ it could as well be written component-by-component ($i = x, y, z$),

$$v_i(t) = \int \int_{\alpha \geq \beta} \mu(\alpha, \beta) \cdot \gamma_{\alpha\beta}[\vec{u}](t) \cdot \chi_{\alpha\beta,i}[\vec{u}](t) d\alpha d\beta. \quad (3)$$

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FIG. 1. Visualization of the switching process of $\gamma_{\alpha\beta}[\vec{u}](t)$. The regions are marked, where the operators are switched to +1, -1 or kept unchanged (older values).

A. The behavior of the switching operator $\gamma_{\alpha\beta}[\circ]$

In the scalar model, the argument of the operator is the (signed) input signal itself. Using the new vector model, the projection of the input vector on the result of the rotational operator $\vec{\gamma}_{\alpha\beta}[\circ]$ is utilized as an argument. This projection is calculated by evaluating the inner product ($\bullet$) as

$$u_{||}(t) = \vec{u}(t) \bullet \vec{\gamma}_{\alpha\beta}[\vec{u}](t) = \|\vec{u}(t)\| \cdot \cos[\angle(\vec{u}(t), \vec{\gamma}_{\alpha\beta}[\vec{u}](t))]. \quad (4)$$

As physical motivation the assumption holds that only this projected part $u_{||}(t)$ is responsible for the switching of the domains. Absolute value and direction of the input vector influence the rotation. Therefore we write

$$\gamma_{\alpha\beta}[\vec{u}](t) = \begin{cases} +1 & : u_{||}(t) > \alpha \\ \gamma_{\alpha\beta}[\vec{u}](t^-) & : \beta < u_{||}(t) < \alpha \\ -1 & : u_{||}(t) < \beta \end{cases} \quad (5)$$

FIG. 2. Switching within the $\vec{\gamma}_{\alpha\beta}$ plane. The regions are marked, where the operators are switched to the new angle $\vec{e}_u(t)$ or kept unchanged (older values).

FIG. 3. Parallel and perpendicular magnetization plus major hysteresis loop of FeCo thin film material. Comparison with simulation ($k = 1.3$).

B. The behavior of the rotational operator $\vec{\gamma}_{\alpha\beta}[\circ]$

The behavior of the rotational operator is modeled symmetrically, which means the straight $\alpha = -\beta$ is an axis of symmetry in the $\vec{\gamma}_{\alpha\beta}$ plane (Fig. 2). This is justified by the fact that the switching operator is signed. The multiplication of both operators in Eq. (2) results in an orientation parallel or antiparallel to the input signal $\vec{u}(t)$. The algorithm for the rotational operator therefore reads as

$$\vec{\gamma}_{\alpha\beta}[\vec{u}](t) = \begin{cases} \vec{e}_u(t) & u_{\chi}(t) > \alpha \vee -u_{\chi}(t) < \beta \\ \vec{\gamma}_{\alpha\beta}[\vec{u}](t^-) & \beta < -u_{\chi}(t) \wedge u_{\chi}(t) < \alpha \end{cases} \quad (6)$$

with the rotation threshold $u_{\chi}(t)$,

$$u_{\chi}(t) = \frac{1}{2}(2\|\vec{u}(t)\|)^k. \quad (7)$$

Here, $\vec{e}_u(t)$ denotes the unity vector in the direction of $\vec{u}(t)$,

$$\vec{e}_u(t) = \frac{\vec{u}(t)}{\|\vec{u}(t)\|}. \quad (8)$$

So far, the parameter k is the only additional parameter of the vector model. It can be imagined as the velocity of the rotational process compared to the switching process. For $k = 1$ the absolute values of the thresholds are the same for both processes. $k > 1$ results in a slower (later) rotation, which is the case for some materials, see for example Fig. 5 below. We call k the **rotational resistance**.

FIG. 4. Trajectory of the tip of the magnetization vector. Simulation and measurement of FeCo thin film material.

FIG. 5. Parallel and perpendicular magnetization plus major hysteresis loop of NiFe thin film material. Comparison with simulation ($k = 3.0$).

C. Properties of the vectorial Preisach operator

The vectorial Preisach operator is a true enhancement of the scalar Preisach operator. When applied to one-dimensional signals, the vectorial operator behaves exactly like the scalar operator. The properties of the scalar operator as congruency property and wipe-out rule¹⁰ also persist. Another great advantage of this kind of generalization is the fact that developments on the classical operator, as for example the modeling of temperature and frequency behavior,¹¹ can directly be applied to the vector operator.

III. COMPARISON OF SIMULATION RESULTS TO VECTOR MEASUREMENTS

The model parameters have been adjusted to the measurements taken by a VVSM. Here, we present results for sputtered thin films of NiFe and FeCo (film thickness is $1.7\mu\text{m}$ and $1.9\mu\text{m}$). The data have been achieved by varying the H-field within the film surface (xy-plane) in the following way: a saturation H-field in y-direction has been turned to zero, so that the remanent magnetization remains. Afterwards, the H-field has been increased in x-direction, while the magnetizations parallel ($M_{\parallel}$) and perpendicular ($M_{\perp}$) are measured as well as simulated, respectively. Additionally, a major hysteresis loop is plotted in Figs. 3 and 5.

The FeCo material shows quite typical characteristics (Fig. 3). The slope of the parallel magnetization $M_{\parallel}$ reminds one of a virgin curve, while the perpendicular magnetization

$M_{\perp}$ tends toward zero. Simulation and measurement do match very well for a rotational resistance of $k = 1.3$. The data in Fig. 4 represent the movement of the tip of the magnetization vector within the magnetization plane. The path of the H-field is the same as described above. Additionally, simulated trajectories for different rotational resistances are plotted to clarify its influence. Figure 5 shows equivalent results for NiFe thin film. Especially interesting is the fact that the slope of $M_{\parallel}$ lies outside the major hysteresis loop. That means that for this material the switching processes happen more easily than the rotation processes. In the model, that results in a high rotational resistance $k = 3.0$.

IV. CONCLUSION

It can be concluded from the presented data that the proposed vector Preisach model offers the possibility to map the hysteresis behavior of quite different ferromagnetic materials. For the chosen devolution of H-fields, a very good match between measured and simulated magnetization trajectory could be achieved.

It is a future task to extend the experiments on different H-field signals like rotational fields. Another important task will be the comparison with VVSM measurements in all three spatial directions. In this context, the anisotropic extension of the model will be important.

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