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A modified Preisach hysteresis operator for the modeling of temperature dependent magnetic material behavior

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In this paper, we present a model for temperature dependent hysteretic nonlinearities with nonlocal memories. This model can be applied to describe hysteretic material behavior. Common applications are ferromagnetic or magnetostrictive materials. Our model consists mainly of a Preisach operator with a continuous Preisach weight function. We choose a weight function which shows a strong correlation between the function's parameters and certain properties of the hysteresis curve. As a new approach, the weight function is written as a function of temperature. The model parameters are customized to a set of symmetric hysteresis curves. We verify our model for magnetic materials with differently shaped hysteresis curves, different temperatures and magnetic field amplitudes. © 2011 American Institute of Physics. [doi:10.1063/1.3562520]

I. INTRODUCTION

For the numerical simulation of transducers and devices, it is essential to utilize appropriate models for the involved materials.^{1,2} In a first step, linear or nonlinear approximations are often used. When materials are involved, which incorporate memory effects, like ferromagnetic, magnetostrictive or piezoelectric materials, the need for models arises, which can reflect this memory.³⁻⁹ For the modeling of such materials, mathematical descriptions like the Preisach operator have been proposed.¹⁰⁻¹² Since the native Preisach operator is static and does not incorporate time or temperature dependent effects, some research on the dynamic extension of the Preisach-Neel model for Stoner-Wohlfarth particle systems has been conducted.^{13,14}

In this paper, we describe a Preisach model with a temperature dependent weight function. There exist different approaches to identifying the weight function of the Preisach plane for a specific material. For piezoelectric materials an approach using a discrete weight function can be found in Ref. 15. The authors of Refs. 16–18 have used Gaussian, Lorentzian and Derivative-Arc-Tangent (DAT) functions to define a continuous weight function for the Preisach plane.

For our work, we utilize the DAT function with a slight modification. This modification makes the parameters more significant for certain properties of the hysteresis curve. Since the temperature mainly influences the saturation and the coercivity field strength, the temperature behavior can fully be represented by two time dependent parameters of the DAT function.

After the mathematical formulation of the model and the changes made for the DAT function, we describe the temperature dependent Preisach operator in Sec. III. In Sec. IV we test our model for two different materials at different temperatures and field amplitudes.

II. HYSTERESIS MODEL

A mathematical operator which describes hysteretic behavior is the Preisach operator. Here, we can give only a brief introduction to this operator, further information can be found in literature.^{11,19} The general formulation for the continuous Preisach hysteresis operator $\hat{\Gamma}$ is

$$f_1(t) = \hat{\Gamma}[u](t) = \iint_{\alpha \geq \beta} \mu_1(\alpha, \beta) \hat{\gamma}_{\alpha\beta}[u](t) d\alpha d\beta, \quad (1)$$

where the time signals $u(t)$ and $f_1(t)$ denote the input and output, respectively. The weight function $\mu_1(\alpha, \beta)$ defines the shape of the hysteresis curve and is extensively discussed in Ref. 18. The operators $\hat{\gamma}_{\alpha\beta}$ can only take the discrete values -1 and 1. They resemble the “memory” of the hysteresis operator and are also often called “switching operators”. The integral is evaluated over the two-dimensional, triangular-shaped Preisach Plane.¹¹

The approach which has been described in Ref. 18 suggests an analytical function with a small number of parameters expressing the continuous weight function. In the aforementioned paper a Derivative-Arc-Tangent (DAT) weight function

$$\mu_1(\alpha, \beta) = \frac{A}{1 + \{[(\alpha + \beta)\sigma]^2 + [(\alpha - \beta - h)\sigma]^2\}^\eta} \quad (2)$$

with four parameters A , h , σ and η has been introduced. In order to make the single parameters more significant to certain properties of the hysteresis curve, like coercivity field strength and saturation polarization, we propose a small variation of the Preisach Operator: we write the parameter A together with a scaling factor s in front of the integral in Eq. (1),

$$f_2(t) = As \iint_{\alpha \geq \beta} \mu_2(\alpha, \beta) \hat{\gamma}_{\alpha\beta}[u](t) d\alpha d\beta. \quad (3)$$

We utilize the slightly modified DAT weight function

$$\mu_2(\alpha, \beta) = \frac{1}{1 + \{(\alpha + \beta)^2 + (\alpha - \beta - h)^2\}^\eta \cdot \sigma^{2\eta}} \quad (4)$$

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FIG. 1. (Color online) Influence of the individual parameters on the shape of the hysteresis curve. The initial parameters are $\sigma = 10$, $A = 1$, $\eta = 1$ and $h = 0.2$. For each curve, one parameter has been altered.

and the scaling factor

$$s = \int_{-0.5}^{0.5} \int_{\beta}^{0.5} \mu_2(\alpha, \beta) d\alpha d\beta. \quad (5)$$

The advantage of these modifications is that the parameters now can clearly be assigned to certain properties of the hysteresis curve. Figure 1 illustrates the influence of the individual parameters on the shape of the hysteresis curve. For each curve, one single parameter has been altered compared to the initial set. It can clearly be noticed that only A influences the value of saturation and that the coercivity field strength mainly changes with h . The parameter σ controls the slope at the point of coercivity and η controls the curvature. For hard magnetic materials, η is significantly higher than for soft magnetic materials.

Since the Preisach model does not account for the reversible part of magnetization, an additional analytic expres-

FIG. 2. (Color online) Hysteresis curves of the same material at different temperatures and amplitudes. Measured curves are solid, simulated ones are dashed.

TABLE I. Parameters for the steel sheet in Fig 2. The magnetization of this material is $M_{\max} = 1.38 \text{ T}$ at a magnetic field of $H_{\max} = 500 \text{ A/m}$ and the coercivity field strength is $H_C = 80.7 \text{ A/m}$ and the remanent magnetization is $M_R = 0.62 \text{ T}$. In order to make the parameters comparable for different materials, the measured curves are always normalized to $2M_{\max}$ and $2H_{\max}$. The parameters for the reversible part as modeled by Eq. (6) are $a = 5.57$, $b = 0.202$ and $c = 0$.

σ	A_{20}	η	h_{20}	$\alpha_A (^{\circ}\text{C}^{-1})$	$\alpha_h (^{\circ}\text{C}^{-1})$
19.9	0.699	1.14	0.168	$-8.64 \cdot 10^{-5}$	$-2.20 \cdot 10^{-4}$

sion f_{rev} can be added to the model output if necessary. For this reason, the function

$$f_{\text{rev}}(t) = a \arctan[bu(t)] + cu(t) \quad (6)$$

has already been proposed before.¹⁸ The model parameters are identified using an Inverse Method. The method and the algorithm for finding appropriate initial conditions can be found in the literature.¹⁸

The form in which the data has to be transferred to the identification algorithm is not fixed. In principle the use of first-order reversal curves (FORC) is possible as well as symmetric minor loops (SML), as both kinds of measurement data sets contain similar information.¹⁶ In our experiments, SML measurements are used, since these data sets are easier to measure.

III. TEMPERATURE DEPENDENCE

The main topic of this work is the inclusion of temperature dependence in the Preisach operator. Since the temperature influences within the considered temperature range ($-40^{\circ}\text{C} - 140^{\circ}\text{C}$) mainly the coercivity field strength and the saturation of magnetic materials, the temperature dependence is modeled by linear expressions of $h(T)$ and $A(T)$. The temperature dependence of the parameter h is described by

$$h(T) = h_{20} + \alpha_h(T - T_{20}), \quad (7)$$

FIG. 3. (Color online) Magnification of the behavior around the coercivity field strength for four different temperatures. Measured curves are solid, simulated ones are dashed.

FIG. 4. (Color online) Measured (solid) and simulated (dashed) curves for a magnetic material with higher remanent magnetization.

where T is the temperature in $^{\circ}\text{C}$, $T_{20} = 20^{\circ}\text{C}$, h_{20} denotes the parameter h at 20°C and α_h is the linear temperature coefficient of h . The term for the parameter A is written in a similar way

$$A(T) = A_{20} + \alpha_A(T - T_{20}). \quad (8)$$

The temperature dependent Preisach operator can then be formulated as

$$f_2(t) = A(T)s(T) \int \int_{\alpha \geq \beta} \mu_2(\alpha, \beta, T) \hat{\gamma}_{\alpha\beta}[u](t) d\alpha d\beta$$

$$\mu_2(\alpha, \beta, T) = \frac{1}{1 + \{(\alpha + \beta)^2 + (\alpha - \beta - h(T))^2\}^{\eta} \times \sigma^{2\eta}}$$

$$s(T) = \int_{-0.5}^{0.5} \int_{\beta}^{0.5} \mu_2(\alpha, \beta, T) d\alpha d\beta. \quad (9)$$

IV. RESULTS

Figure 2 shows the hysteresis curves of some soft magnetic steel plate at different temperatures and different magnetic field amplitudes. It also compares the measured hysteresis curves with the model output and proves that the relevant material properties can be modeled sufficiently. The complete parameter set for the material in Fig. 2 is given in Table I. Figure 3 shows a magnification of the area around the coercivity field strength of the same materials outer loop, but at four different temperatures. It proves that also the gradient of the coercivity field strength can be modeled precisely by Eqs. (7) and (8). Figure 4 contains the same comparison for a magnetic material with much higher remanent magnetization and proves the efficiency of the model

TABLE II. Parameters for the curve in Fig. 4. The maximum magnetization of this material is $M_{\max} = 1.47 \text{ T}$ at a magnetic field of $H_{\max} = 50 \text{ A/m}$, the coercivity field strength is $H_C = 10.0 \text{ A/m}$ and the remanent magnetization is $M_R = 1.31 \text{ T}$. The reversible part can be neglected for this material.

σ	A_{20}	η	h_{20}	$\alpha_A (^{\circ}\text{C}^{-1})$	$\alpha_h (^{\circ}\text{C}^{-1})$
19.9	1.01	1.41	0.243	-1.73×10^{-4}	-1.36×10^{-4}

for quite different types of hysteresis curves. The complete parameter set for this material is given in Table II.

V. CONCLUSION

In this paper, we showed a new approach to modeling temperature behavior with the Preisach operator. The model is based on the continuous DAT weight function. We found that by extending only two parameters of the weight function to linear functions of temperature, the temperature dependant material behavior can be modeled properly. The model has been tested for different shapes of hysteresis curves and different temperatures and magnetic field amplitudes as well.

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