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Dynamic vector hysteresis modeling

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Abstract

The possibility of considering dynamic effects in three vector hysteresis models is investigated. The friction model of oriented Preisach operators which rotate due to the torque exerted by the external field, the coercive spheres model, the 3D analogue of the classical Preisach model, and a further collective model based on micromagnetic analogy are considered. Furthermore, the "external" dynamic generalization of the static hysteresis models is introduced for the vector case.

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Keywords: Vector hysteresis; Preisach model; Dynamic effects

1. Introduction

The classical Preisach model accurately and efficiently describes scalar hysteresis, where the magnetic field strength is always parallel to magnetization. This is the case when the material is isotropic, the direction of excitation is constant in time and the shape of the body is symmetrical with respect to this direction. The field strength and magnetization vectors are generally not parallel to each other inside a ferromagnetic body, raising the need for vector models. This occurs in isotropic materials due to remanence (anisotropy induced by magnetic history) while anisotropic materials are intrinsically characterized by different magnetic properties in different directions.

Three approaches for vector hysteresis modeling are presented in this paper: the friction model which is based on the superposition of classical Preisach operators and a rotation scheme instead of cross-coupling functionals between scalar models identified for the principal axes [1]; the coercive spheres model, based on essentially vector operators; and a micromagnetic analogy (a 3D simulation of Ewing's classical experiment).

2. The friction model

The friction vector hysteresis model consists of n scalar (classical) Preisach operators, endowed with orientation $\boldsymbol{p}_k$, with $p_k = 1$, each following the input variation with a different lag determined by a friction-like mechanism [2]. The magnitude of the individual operator output is given by

$$M_k = \mathrm{P}(H\,cos\,\theta_k) = \mathrm{P}(\boldsymbol{H}\cdot\boldsymbol{M}_k) = \mathrm{P}(\boldsymbol{H}\cdot\boldsymbol{p}_k), \tag{1}$$

where P stands for the classical Preisach operator, H is strength of the applied field $\boldsymbol{H}$ and θ_k the angle between $\boldsymbol{H}$ and $\boldsymbol{p}_k$. This angle is determined by the equilibrium between a driving torque $\boldsymbol{M}_k \times \boldsymbol{H}$ tending to align the magnetization with field strength and a friction-like resisting torque, proportional to ${M_k}^{3/2}\,(M_S–M_k)^{1/2}$, chosen to comply with the experimental fact that at saturation magnetization is parallel to field strength (in the static case). The orientation changes when the driving torque

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overcomes the resisting one leading to

$$\theta_k : \begin{cases} \text{unchanged} \quad \text{if } |\sin\theta_k| < \xi_k \frac{H_S}{|H|}\sqrt{\frac{|M_k|}{M_S}\left(1-\frac{|M_k|}{M_S}\right)} \\ |\sin\theta_k| = \xi_k \frac{H_S}{|H|}\sqrt{\frac{|M_k|}{M_S}\left(1-\frac{|M_k|}{M_S}\right)} \text{ otherwise,} \end{cases} ; \quad k=\overline{0,n}, \tag{2}$$

where H_S is the saturation field strength. The magnetization vector lies in the plane defined by the new position of the applied field strength and the old position of magnetization, obeying

$$\begin{aligned} &\boldsymbol{M}'_k \cdot (\boldsymbol{H} \times \boldsymbol{M}_k) = 0, \\ &\frac{\boldsymbol{M}'_k \cdot \boldsymbol{H}}{M'_k H} = \cos\theta_k, \end{aligned} \tag{3}$$

where $\boldsymbol{M}_k$ is the old, $\boldsymbol{M}'_k$ the new magnetization vector of the operator k and θ_k is determined by iterative search until both Eqs. (1) and (2) are satisfied. Additional lag due to dynamic effects can be introduced at two points: the scalar operators can be dynamic hysteresis operators and the rotation process can also be damped with respect to the input variation rate.

3. The coercive spheres model

A natural vector generalization of the classical Preisach model is a 3D static vector hysteresis model built as a set of spherical elementary vector operators, defined by a mean interaction field $\boldsymbol{H}_m^k$ (position of the center of the sphere in the input phase space) and coercivityH_c^k (radius of the sphere) [3]. The outputs of these operators are vectors $\boldsymbol{M}^k$ with constant magnitude (in fact $M^k = 1$ for each k). The vector $\boldsymbol{M}^k$ is pointing in the direction of $\boldsymbol{H} - \boldsymbol{H}_m^k$ if $\boldsymbol{H}$ lies outside the sphere (Fig. 1) and preserves the orientation it had at the moment it entered the sphere as long as the tip of $\boldsymbol{H}$ lies inside it. The output of the model is the weighted sum of the elementary operator outputs. The operators are distributed with respect to $\boldsymbol{H}_m^k$ and H_c^k, similar to the case of the classical Preisach model. This is also a dissipative model, as the elementary operators can be regarded as friction elements that hinder the modification of their output until the driving force prevails (the tip of $\boldsymbol{H}$ leaves the sphere). A similar, yet somewhat more complex, model also emerges as the generalization of the Stoner-Wohlfahrt model [4,5]. In analogy with the rate-dependent generalization of the classical Preisach model [6], replacing the sudden jump of the Preisach operator output vector with a rotation at finite rate, a dynamic vector hysteresis model can be obtained (Fig. 2). The magnetization vector rotates towards the direction of $\boldsymbol{H} - \boldsymbol{H}_m^k$ with angular velocity

$$\boldsymbol{\omega}_k = \begin{cases} 0 \quad \text{if } |\boldsymbol{H} - \boldsymbol{H}_m^k| \leqslant H_c^k, \\ q\boldsymbol{M}^k \times (\boldsymbol{H} - \boldsymbol{H}_m^k) \quad \text{if } |\boldsymbol{H} - \boldsymbol{H}_m^k| > H_c^k, \end{cases} \tag{4}$$

where q is a model parameter. It can be identified by fitting simulated dynamic characteristics to measured ones. It might depend on operator parameters (e.g. H_c^k). In the plane defined by $\boldsymbol{M}^k$ and $\boldsymbol{H} - \boldsymbol{H}_m^k$, Eq. (4) becomes

$$\frac{\mathrm{d}\theta_k}{\mathrm{d}t} = \begin{cases} 0 \quad \text{if } |\boldsymbol{H} - \boldsymbol{H}_m^k| \leqslant H_c^k, \\ -q|\boldsymbol{H} - \boldsymbol{H}_m^k| \sin\theta_k \quad \text{if } |\boldsymbol{H} - \boldsymbol{H}_m^k| > H_c^k. \end{cases} \tag{5}$$

For the numerical examples in the sequel, a 2D model consisting of $n_a \times n_t \times n_t$ elementary operators has been

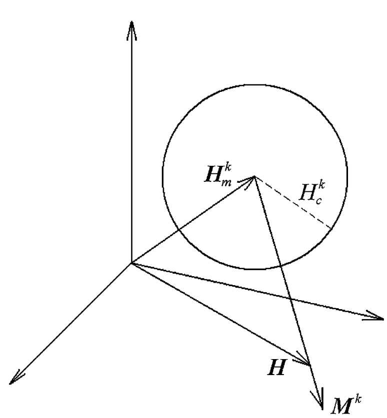

Fig. 1. Elementary static vector operator.

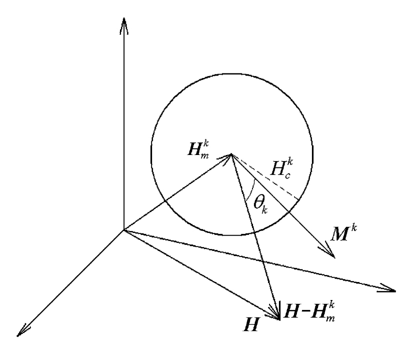

Fig. 2. Elementary dynamic vector operator.

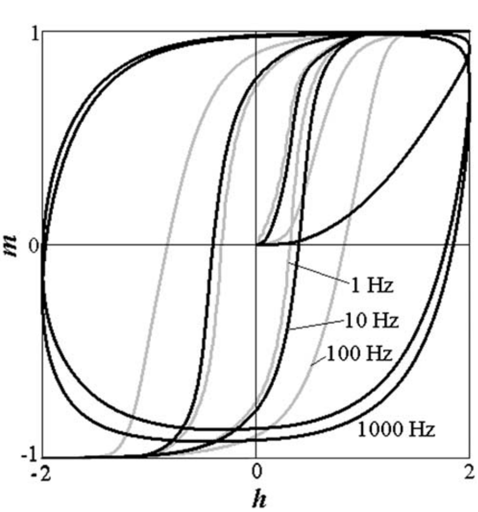

Fig. 3. Dynamic vector model in alternating operation at various frequencies.