

Identification of Biaxially Anisotropic Vector Play Model for Representation of Pinning Field Distribution

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A biaxially anisotropic vector hysteresis model is developed by the superposition of scalar play models. Its identification method was derived analytically. BH loops of non-oriented silicon steel sheets are accurately reconstructed along the rolling, transverse, and 45-degree directions. The proposed model is applied to the representation of anisotropic pinning field distribution for physical magnetization analysis.

Index Terms— anisotropic vector hysteresis, biaxial anisotropy, identification, pinning field

I. INTRODUCTION

BOTH Preisach and play models have their vector versions constructed by the superposition of scalar models [1-3]. They have not only mathematical clarity but also some physical aspects reflecting the polycrystalline structure of magnetic material. Based on the physical background, the vector play model of superposition type is applied to the decomposition of the pinning field components from the measured MH loop to give a pinning field distribution to a physical magnetization model [4][5]. Mayergoyz has formulated an anisotropic vector hysteresis model of superposition type in a general form using the spatial Fourier expansion [1]. However, the identification of anisotropic components was not very easy.

Ref. [5] developed a uniaxially anisotropic superposition model by deriving its analytical identification method to construct an anisotropic distribution of the pinning field. This model was applied to a physical magnetization analysis, which successfully improved the prediction of stress dependence of hysteresis loss. However, silicon steel has a cubic anisotropy, which appears as a biaxial anisotropy within the sheet plane.

This article develops a biaxially anisotropic vector play model of superposition type and derives its identification method analytically.

II. ANISOTROPIC VECTOR PLAY MODEL

A. Anisotropic Vector Model Based on Superposition

A hysteretic function from input B to output H is represented by a scalar play model as

$$H = F(B) + \int_{+0}^{B_s} f(\zeta, p_\zeta(B)) d\zeta \quad (1)$$

where F and f are single-valued functions called shape functions, and B_s is the saturation magnetic flux density. The play hysteron operator $p_\zeta(B)$ with half-width ζ is given as

$$p_\zeta(B) = \max(\min(p_\zeta^0, B + \zeta), B - \zeta) \quad (2)$$

where p_ζ^0 is p_ζ at the previous time-point.

A vector hysteresis model with biaxial anisotropy is constructed by the superposition of scalar models as

$$\mathbf{H} = \int_{-\pi/2}^{\pi/2} \mathbf{e}_\varphi [P_{20}(B_\varphi) + P_{22}(B_\varphi) \cos 2\varphi + P_{24}(B_\varphi) \cos 4\varphi] d\varphi \quad (3)$$

$$B_\varphi = \mathbf{e}_\varphi \cdot \mathbf{B} \quad (4)$$

where $\mathbf{B}$ is the magnetic flux density, $\mathbf{H}$ is the magnetic field, φ is the azimuth angle, and $\mathbf{e}_\varphi$ is the unit vector in the φ -direction; P_{20} , P_{22} , and P_{24} are the scalar hysteretic functions given by the play or Preisach model. The unidirectional property of (3) along the φ -direction is given as

$$Y_\varphi(X) = P_{10}(X) + P_{12}(X) \cos 2\varphi + P_{14}(X) \cos 4\varphi \quad (5)$$

B. Identification Method

Mayergoyz [1] gave an analytical identification method to determine P_{20} from measured P_{10} for the Preisach model, which can be applied to the play model [3]. Ref. [5] gives a similar method to identify P_{22} from measured P_{12} for the play model. So far, no analytical method to identify P_{24} from P_{14} was known. This article derives an analytical identification method to determine P_{24} for the play model, which is applicable to the Preisach model.

A function below is defined for the identification,

$$T_{ik}(\zeta, p) = \begin{cases} F_{ik}(p) + \int_{+0}^{\zeta} f_{ik}(\xi, p) d\xi & (0 < \zeta) \\ F_{ik}(p) & (\zeta = 0) \end{cases} \quad (6)$$

where $i = 1, 2$ and $k = 0, 2, 4$. T_{1k} is given from the shape functions F_{1k} and f_{1k} of P_{1k} . Using T_{1k} , F_{1k} and f_{1k} of P_{1k} ($k = 0, 2, 4$), T_{2k} is obtained by solving the integral equation below:

$$T_{1k}(\zeta, p) = \int_{-\pi/2}^{\pi/2} \cos \psi \cos(k\psi) T_{2k}(\zeta \cos \psi, p \cos \psi) d\psi \quad (7)$$

The analytical solutions for T_{20} [3] and T_{22} [5] are given as:

$$T_{2k}(\lambda p, p) = \frac{1}{\pi} \int_0^{\pi/2} \tilde{T}_{1k}(\lambda p \cos \varphi, p \cos \varphi) d\varphi \quad (8)$$

$$\tilde{T}_{10}(\lambda p, p) = T_{10}(\lambda p, p) + p \frac{dT_{10}(\lambda p, p)}{dp} \quad (9)$$

$$\tilde{T}_{12}(\lambda p, p) = 3T_{12}(\lambda p, p) + p \frac{dT_{12}(\lambda p, p)}{dp} \quad (10)$$

where $\lambda = \zeta/p$.

We have derived an analytical solution for T_{24} as

$$T_{24}(\lambda p, p) = \frac{p}{\pi} \int_0^p \int_0^{\pi/2} \frac{\tilde{T}_{14}(\lambda s \cos \varphi, s \cos \varphi)}{s^2} d\varphi ds \quad (11)$$

$$\tilde{T}_{14}(\lambda p, p) = 15T_{14}(\lambda p, p) + 9p \frac{dT_{14}(\lambda p, p)}{dp} + p^2 \frac{d^2T_{14}(\lambda p, p)}{dp^2}. \quad (12)$$

The detailed derivation will be given in the full paper.

From the identified T_{2k} , f_{2k} and F_{2k} are given as

$$f_{2k}(\zeta, p) = \frac{\partial T_{2k}(\zeta, p)}{\partial \zeta}, F_{2k}(p) = T_{2k}(0, p). \quad (13)$$

III. COMPUTATIONAL RESULTS

A. Vector Hysteretic Property of Silicon Steel Sheet

A non-oriented silicon steel sheet JIS: 350A300 is measured along the rolling direction (RD), the transverse direction (TD), and the 45-degree direction (45D). The developed identification method determines P_{24} from P_{14} as well as P_{20} and P_{22} . Fig. 1(a) shows the reconstructed BH loops along the RD and TD, where the anisotropic property is accurately reconstructed. Fig 1(b) shows the BH loops reconstructed by the biaxial and uniaxial vector models along the 45D, where the biaxial model is more accurate than the uniaxial one.

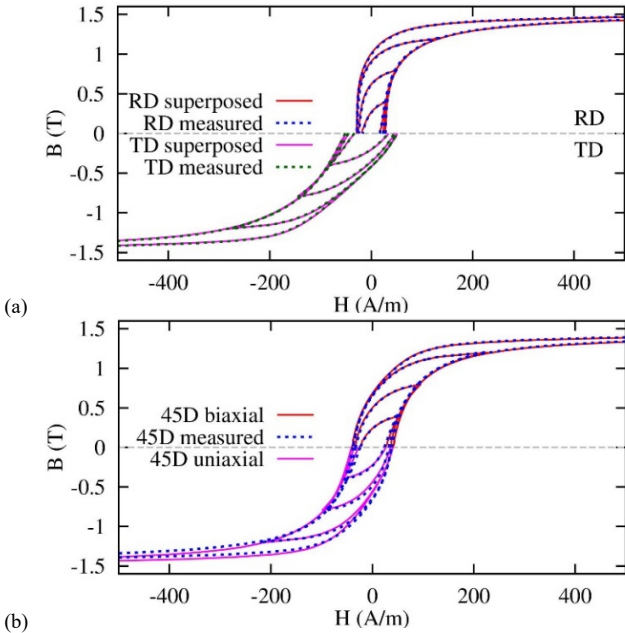


Fig. 1. BH loops simulated by the anisotropic vector play model: (a) along RD and TD and (b) along 45-degree direction.

Application to magnetization analysis

The multi-domain particle model (MDPM) is a physical magnetization model [4], which can predict the increase in the hysteresis loss of silicon steel sheets due to compressive stress without using measured data under the stress. The MDPM yields the hysteretic property by the superposition of hysteretic properties of multi-domain particles. To represent the anisotropic pinning field in each particle, the pinning field components are extracted by subtracting the anhysteretic components from the MH loops of P_{20} , P_{22} , and P_{24} . Figs. 2(a)

shows the extracted pinning field components normalized by the anisotropy field, which are denoted as P_{p20} , P_{p22} , and P_{p24} . Fig. 2(b) shows the pinning field components superposed by (3) using P_{p20} , P_{p22} , and P_{p24} , which coincide with the pinning field components extracted from P_{10} , P_{12} , and P_{14} . Even though the distribution P_{p14} is smaller than P_{p10} and P_{p12} , the decomposed component P_{p24} is rather large compared with P_{p20} and P_{p22} .

A preliminary analysis using the MDPM with the biaxially anisotropic pinning field is carried out to predict the loss increase along the 45D due to the induced anisotropy [4] caused by the compressive stress of 50 MPa [Fig. 3]. Detailed discussions will be presented in the full paper.

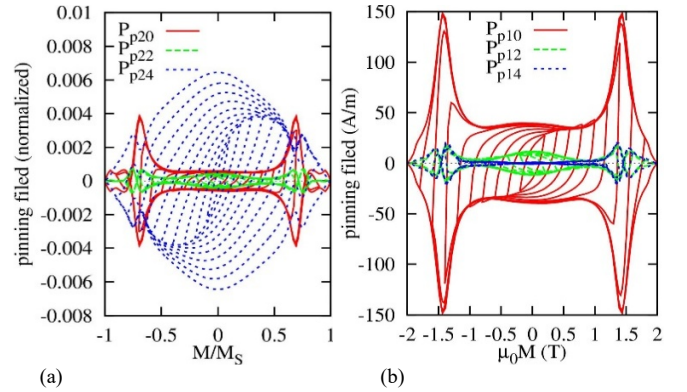


Fig. 2. Pinning fields: (a) P_{p20} , P_{p22} , and P_{p24} (normalized by anisotropy field) and (b) P_{p10} , P_{p12} , and P_{p14} .

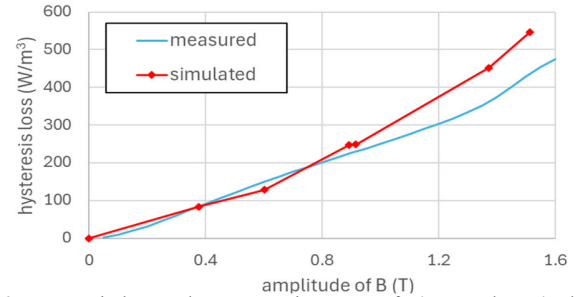


Fig. 3. Hysteresis loss under compressive stress of 50 MPa along 45-degree direction predicted by MDPM using biaxially anisotropic pinning field.

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