ACCURATE IDENTIFICATION OF BH-LOOPS FROM MEASUREMENT USING WIDE RING SPECIMEN

T. Matsuo

Kyoto University, Japan
Email_matsuo.tetsuji.5u@kyoto-u.ac.jp

Keywords: Analytical identification, hysteresis loop, ring specimen.

Abstract

An analytical formulation is developed for identifying the hysteretic property of magnetic material from the measured current-flux property of a ring specimen. A computational example shows that the proposed method can reconstruct the hysteretic property more accurately than conventional approximations.

1 Introduction

The magnetic property of core material is often measured using a ring specimen. It is recommended that the ratio of the outer radius to the inner one should be equal to or less than 1.1 [1, 2] to avoid the field nonuniformity inside the ring specimen. However, it is sometimes difficult to manufacture a narrow ring sample. Several methods have been proposed to reconstruct an accurate BH curve taking account of the nonuniformity [2]. However, its numerical procedure is often cumbersome and the application to identify hysteresis loops is not straightforward.

This article proposes an analytical formulation for accurately identifying BH loops using a wide ring specimen.

2 Identification of BH curves

2.1 Conventional identification of BH curves

The magnetic property is supposed to be $B = f(H)$. This property is identified from measurement using a ring specimen having a rectangular cross-section with the inner radius a, the outer radius b, thickness w, and the number of primal and secondary windings N_1 and N_2. When the excitation current is I, the magnetic field at the radius r is given as $H = N_1 I / 2\pi r = i / r$, where $i = N_1 I / 2\pi$. The flux linkage $\Phi = wN_2\int_a^b f(i/r)\mathrm{d}r$ is obtained by measurement. Hence, $\varphi = \Phi / wN_2$ is given as the function of i, which is written as

$$\varphi(i) = \int_a^b f(i/r)\mathrm{d}r \,. \qquad (1)$$

The averaged B is given by $B_{\mathrm{ave}} = \varphi(i) / (b-a)$.

By setting the average path length $\pi(a+b)$ or $2\pi(b-a) / \log(b/a)$, averaged H corresponding to B_{ave} is give as

$$H_{\mathrm{avep}} = 2i / (a+b) \,. \qquad (2)$$

$$H_{\mathrm{avef}} = i \log(b/a) / (b-a) \,. \qquad (3)$$

Conventionally, relation (H_{avep}, B_{ave}) or (H_{avef}, B_{ave}) has been used as the core property. This article calls the former “mean path approximation” and the latter “mean field approximation”.

2.2 Accurate Identification of BH curves

The differentiation of Eq. (1) gives

$$\mathrm{d}\varphi(i)/\mathrm{d}i = \int_a^b \mathrm{d}f(i/r)/\mathrm{d}i\, \mathrm{d}r = \int_a^b f'(i/r)/r\, \mathrm{d}r \,. \qquad (4)$$

Using $H = i/r$, Eqs. (1) and (4) are rewritten as

$$\varphi(i) = \int_{Ha}^{Hb} f(H)\, i/H^2 \mathrm{d}H \,, \qquad (5)$$

$$\mathrm{d}\varphi(i)/\mathrm{d}i = [f(H)/H]_{Hb}^{Ha} + \int_{Hb}^{Ha} f(H)/H^2\, \mathrm{d}H \,. \qquad (6)$$

where $H_a = i/a$ and $H_b = i/b$. From Eqs. (5) and (6)

$$f(H_a) / H_a - f(H_b) / H_b = \mathrm{d}\varphi(i)/\mathrm{d}i - \varphi(i) / i \qquad (7)$$

is obtained. By setting

$$F(i) = \mathrm{d}\varphi(i)/\mathrm{d}i - \varphi(i) / i \qquad (8)$$

$$c = a/b = H_b/H_a\ (< 1) \qquad (9)$$

Eq. (7) is rewritten as

$$f(H_a) / H_a = f(cH_a) / cH_a + F(i) \,. \qquad (10)$$

Replacing i by $c^n i$ in Eq. (10), one obtains $f(c^n H_a) / c^n H_a = f(c^{n+1} H_a) / c^{n+1} H_a + F(c^n i)$. Consequently,

$$f(H_a) / H_a = f(c^2 H_a) / c^2 H_a + F(ci) + F(i)$$

$$= \ldots = \mu_1 + \Sigma_{n=0}^{\infty} F(c^n i) \,. \qquad (11)$$

is derived, where $f(H) / H \to \mu_1$ $(H \to 0)$.

2.3 Identification of hysteresis loops

The hysteretic BH curve depends on the amplitude H_m of the magnetic field as

$$B = f(H, H_m) \ . \tag{12}$$

The amplitude of the exciting current is denoted by I_m and $i_m = N_1 I_m / 2\pi$. Using a constant α ($-1 \le \alpha \le 1$), the exciting current i is written as $i = \alpha i_m$.

The flux linkage $\Phi = wN_2 \int_a^b f(i/r,\ i_m/r)\mathrm{d}r$ is obtained by measurement. Hence, $\Phi / wN_2 = \int_a^b f(i/r,\ i_m/r)\mathrm{d}r$ is given as the function of i_m and $i = \alpha i_m$, which is written as

$$\int_a^b f(\alpha i_m/r,\ i_m/r)\mathrm{d}r = \varphi(\alpha i_m,\ i_m) = \varphi_\alpha(i_m) \ . \tag{13}$$

By setting

$$F_\alpha(i_m) = \mathrm{d}\varphi_\alpha(i_m)/\mathrm{d}i_m - \varphi_\alpha(i_m) / i_m \tag{14}$$

a similar relation to Eq. (11)

$$f(\alpha H_a,\ H_a) / H_a = \mu_{\alpha 1} + \Sigma_{n=0}^{\infty} F_\alpha(c^n i_m) \ . \tag{15}$$

is derived, where $H_a = i_m/a$ and $f(\alpha H_a,\ H_a) / H_a \to \mu_{\alpha 1}$ ($H_a \to 0$).

By changing α within $-1 \le \alpha \le 1$, hysteretic BH curves $B = f(H, H_m)$ can be obtained.

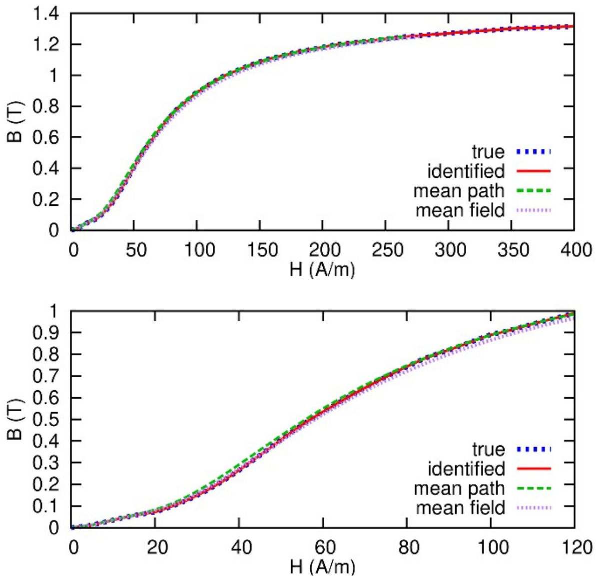

Figure 1: Normal magnetization curve: (a) overall and (b) enlarged views.

3 Computational results

Measured BH loops of non-oriented steel sheet JIS: 50A470 are used as the reference property (12). Setting c =0.5, flux $\varphi_\alpha(i_m)$ is calculated as Eq. (13). Even though Eq. (15) is an analytical expression, its calculation requires numerical techniques. For example, after obtaining the hysteretic property $\varphi(i,\ i_m)$, it is necessary for the identification procedure to represent $\varphi(i,\ i_m)$ by a hysteresis model. We used the play model [3] to represent i-φ loops accurately for arbitrary i_m and αi_m.

The reconstructed normal magnetization curve and BH loops are shown in Figs. 1 and 2. The proposed identification method gives more accurate BH curves than the conventional method using the mean path and field approximations. In addition, the obtained ranges of H_{avep} and H_{avef} are narrow because they are smaller than field H_a at $r = a$. When $F(i)$ or $F_\alpha(i)$ is positive (negative), the mean path (field) approximation becomes inaccurate where $B > 0$. When $c = 0.5$, the summation in (11) and (15) up to $n = 10$ is sufficient. When c is near 0.9, the convergence of summation is slow, and conventional approximations have sufficient accuracy.

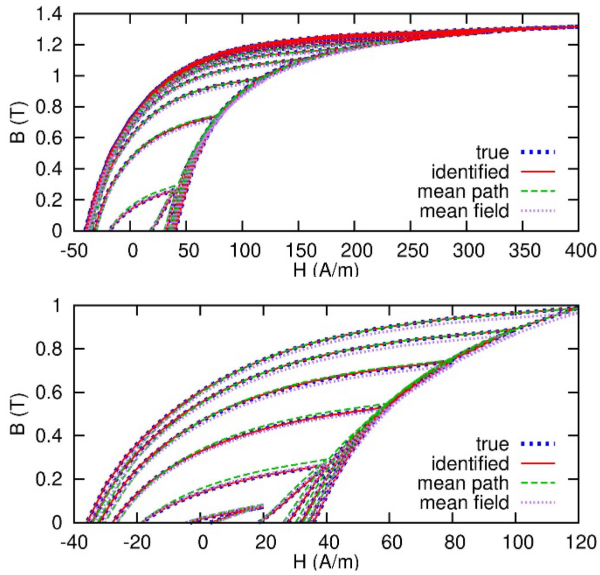

Figure 2: BH loops: (a) overall and (b) enlarged views.

Acknowledgements

The author thanks Mr. Hiroyasu Ito, M.S. student, Kyoto University, Japan, for his assistance in developing the calculation code. This study was supported in part by the MEXT Program for the Creation of Innovative Core Technology for Power Electronics, Grant Number JPJ009777.

References

[1] F. Fiorillo, Characterization and Measurement of Magnetic Materials, Elsevier (2005)

[2] T. Nakata, N. Takahashi, K. Fujiwara, M. Nakano, Y. Ogura, K. Matsubara, "An improved method for determining the DC magnetization curve using a ring specimen," IEEE Trans. Magn. **28**, pp. 2456-2458 (1992)

[3] T. Matsuo, M. Shimasaki, "An identification method of play model with input-dependent shape function," IEEE Trans. Magn., **41**, pp. 3112-3114 (2005)