B and H sensors for 3-D magnetic property testing

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Abstract. One and two-dimensional hysteresis properties are normally used to characterize soft magnetic materials. However, the results are not informative enough to disclose three-dimensional (3-D) hysteresis behavior under vector excitations. This paper presents a 3-D sensing house for measuring the 3-D property of soft magnetic materials. The fabrication, construction, and calibration are discussed in detail. Test results of 3-D magnetic flux density **B** and field strength **H** loci of soft magnetic composite material are presented.

Keywords: 3-D magnetic property, vector hysteresis loci, B and H search coils

1. Introduction

Hysteresis behavior of magnetic materials under vector excitations has not been extensively studied. In order to design and optimize innovative electromagnetic devices using novel soft magnetic materials which are subjected to time-varying three-dimensional (3-D) vector magnetic fields, experimental data and models which can faithfully describe 3-D hysteresis behavior are desired by engineers. In order to characterize the materials properties and elucidate the mechanisms of magnetization, 3-D vector hysteresis property must be measured. This paper presents, in detail, the design, fabrication, and calibration of a sensing box for

measuring 3-D magnetic properties, and the 3-D magnetic flux density $\mathbf{B}$ vector and field strength $\mathbf{H}$ vector loci in a soft magnetic composite are presented.

2. 3-D magnetic property measurement system

A 3-D magnetic property measurement system for cubic sample has been successfully built [1, 2]. Briefly, the system consists of a 3-D magnetic circuit to guide the magnetic fluxes along the orthogonal x -, y -, and z -axes, a data acquisition system, three groups of excitation coils, and a feedback control system comprising a control unit and three high power amplifiers. As a result, various loci of the rotating flux density $\mathbf{B}$ vector, for example, circular or elliptical, can be obtained. A cubic sample is located at the center of the tester. Fig. 1 shows the schematic diagram of the system.

3. Design and Fabrication of $\mathbf{B}$ and $\mathbf{H}$ sensing house

Consider a cubic sample of a soft magnetic material uniformly magnetized by the 3-D magnetic field in the 3-D tester. At the sample surface, the normal component of the magnetic flux density $\mathbf{B}$ is always continuous, and the tangential component of the magnetic field strength $\mathbf{H}$ is also continuous if there is no current flowing at the surface. If axes of the cubic sample align with the orthogonal axes of the tester, the three components of $\mathbf{B}$ and $\mathbf{H}$ can be obtained by measuring the normal components of $\mathbf{B}$ and the tangential components of $\mathbf{H}$ at the six surfaces of the cubic sample. Six flat coils, known as H coils, are located at the centre of the surfaces of a cubic sample, as shown in Fig. 2, to measure the magnetic field $\mathbf{H} = H_x \mathbf{i} +$

$H_y\mathbf{j} + H_z\mathbf{k}$, and three orthogonal coils around the sample, known as B coils, are used to measure the magnetic flux density $\mathbf{B} = B_x\mathbf{i} + B_y\mathbf{j} + B_z\mathbf{k}$ inside the sample. To improve the field uniformity inside the sample, hence, the measurement accuracy, six guard pieces cut from the same sample material are placed around the sample with their isotropic directions aligned with those of the sample. The 3-D finite element simulation has proved the improvement of field uniformity. The core loss of the sample can be calculated from the measured $\mathbf{B}$ and $\mathbf{H}$ by

$$P_t = \frac{1}{T\rho_m} \int_0^T \mathbf{H} \cdot \frac{d\mathbf{B}}{dt} dt \quad (1)$$

where T is the time period of magnetization and ρ_m the mass density.

Each H coil is wound around a thin bakelite former using 0.05 mm enamelled wire. To eliminate the electromotive force (emf) induced by the field component perpendicular to the sample surface during the data analysis, a planar correction coil is embedded in each H coil, as shown in Fig. 2. The correction coils can also be regarded as sensors to measure the $\mathbf{B}$ field. It has been verified that both the results calculated from the B coils wound around the sample and the correction coils are agreement very well, and therefore the correction coils embedded in the H coils can be used for measuring the $\mathbf{B}$ in the sample. In practice, six H coils are integrated to form a rigid cubic B and H sensing house, and the H coils located at the opposite surfaces are connected in series. The sample can be easily placed inside the B and H sensing house.

4. Calibration of H and B sensors

The calibration was performed in a long solenoid. Due to the inevitable gaps between the adjacent turns and irregularities, the emf induced in an H coil is the superposition of two components due to the normal and tangential components of the time-varying magnetic field

at the sample surface. It is the reason that the correction coil is embedded in the H coil to find the emf induced by normal component at the sample surface. The emf component induced by tangential component can be corrected by taking the emf induced in the embedded correction coil into account.

The H sensing house must be calibrated before they can be employed as a sensor to measure **H** field. Applying a uniform AC magnetic field, generated by a long solenoid, parallel to the x -axis of the sensing house, the induced emfs in the coils for the x , y , z -components, U_x^x , U_x^y , U_x^z , can be measured. The dependence of the emfs on the generated magnetic field, H_x , is governed by the Faraday's law,

$$U_x^i = -\mu_0 K_x^i \frac{dH_x}{dt} \quad (i = x, y, z) \quad (2)$$

The coil coefficients for the x -axis, K_x^i , can then be readily obtained. Similarly, K_y^i and K_z^i for the y - and z -axes. By using this calibration method, the coefficients for the B coils, C_x^i , C_y^i , C_z^i and the correction coils, N_x^i , N_y^i , N_z^i can be obtained ($i = x, y, z$).

When the sample is placed into the sensing house and subjected to a magnetic field, the emfs for the x , y , z , directions can be expressed as

$$\begin{cases} E_x = -\mu_0 \left(K_x^x \frac{dH_x}{dt} + K_y^x \frac{dH_y}{dt} - \frac{K_z^x}{\mu_0 N_z^x} V_x \right) \\ E_y = -\mu_0 \left(-\frac{K_x^y}{\mu_0 N_x^y} V_y + K_y^y \frac{dH_y}{dt} + K_z^y \frac{dH_z}{dt} \right) \\ E_z = -\mu_0 \left(K_x^z \frac{dH_x}{dt} - \frac{K_y^z}{\mu_0 N_y^z} V_z + K_z^z \frac{dH_z}{dt} \right) \end{cases} \quad (3)$$

where V_x , V_y , V_z are the emfs in the correction coils embedded in the H_x , H_y , and H_z coils, respectively. The magnetic field at the sample surfaces, H_x , H_y , H_z , can be obtained by solving equation (3). Strictly speaking, the flux density components, B_x , B_y , and B_z , should also be obtained using a similar procedure of (3). Because the planar correction coils have only a few

turns and the area for the tangential component is rather small, the $\mathbf{B}$ components were calculated simply using

$$\mathbf{B} = -\left(\frac{1}{N_x} \int V_y dt\right) \mathbf{i} - \left(\frac{1}{N_y} \int V_z dt\right) \mathbf{j} - \left(\frac{1}{N_z} \int V_x dt\right) \mathbf{k} \quad (4)$$

5. Experimental results

The sample studied in this work is a soft magnetic composite material with cubic shape. It is made of highly pure iron powders with a surface coating to ensure low eddy currents. Fig. 3 plots the $\mathbf{B}$ and $\mathbf{H}$ loci when $\mathbf{B}$ locus is controlled to lie at a spherical surface. The results demonstrate that the calibration and calculation procedures can effectively compute $\mathbf{H}$ and $\mathbf{B}$. Fig. 4 plots the $\mathbf{B}$ and $\mathbf{H}$ loci when the $\mathbf{B}$ loci are controlled to be a circle with a magnitude of 1.3 T at 50 Hz in the xoy -, $yo z$ -, and zox -planes, respectively. Their projections are also plotted. The power losses are 7.3 W/kg for xoy -plane, 14.1 W/kg $yo z$ -plane and 12.3 W/kg zox -plane.

6. Conclusion

A rigid and convenient sensing house integrating six H coils, in which the planar correction coils are imbedded, was fabricated and calibrated for characterizing 3-D magnetic properties of cubic samples of soft magnetic materials. A controlled spherical $\mathbf{B}$ locus and its corresponding $\mathbf{H}$ locus are presented to demonstrate the capability of the 3-D magnetic property measurement system. Using this system, the round $\mathbf{B}$ loci lying in three orthogonal

planes and their $\mathbf{H}$ loci were measured, and the corresponding power losses were calculated by the Poynting's theorem.

References

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Figure captions

Fig. 1. Schematic diagram of system.

Fig. 2. Arrangement of the sample and H coils (left side) and structure of H coil (right side).

Fig. 3. A controlled spherical B locus (left side) and the corresponding H locus (right side).

Fig. 4. Controlled B loci (left side) lying in the xoy, yoz, zox-planes, and their corresponding H loci (right side).

Figure 1

Figure 2

Figure 3

Figure 4