Calibration of the Novel Sensing Structure in Three-Dimensional Magnetic Properties Measurement

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Abstract —A novel sensing structure with combined *B* (magnetic flux density) and *H* (magnetic field strength) sensing coils is used in three dimensional (3-D) magnetic properties testing system. To guarantee the experimental precision and accurately analyze the 3-D magnetic properties, comprehensive calibration and compensation of the sensing structure must be systemically fulfilled. This paper presents the construction and calibration of the surface *B-H* sensing coils, and the effective correction of eliminating errors caused by misalignment of sensing coils and nonessential stray coupling of the 3-D magnetic excitation structures. Also, magnetic properties of a soft magnetic composite (SMC) material specimen are measured and analyzed in alternating and 3-D magnetizations.

I. INTRODUCTION

3-D magnetic properties tester consists of excitation structure and sensing structure. Three orthogonal square frame yokes and three pairs of core poles wrapped with excitation windings are made up of the excitation structure [1]. The original sensing structure was composed of six cross-type surface *H* coils and three *B* coils winding around the cubic specimen. The *H* coil size was approximate equal to that of the specimen side surface; hence the magnetic field at the measured area is not uniform since demagnetization factor [2]. In this paper, a *B-H* combined sensing coil was designed to be small, thin and consistent. Comprehensive calibrations were carried out in a long solenoid and 3-D tester. Accurate coil coefficient matrix (3 × 3) of the sensing coils was obtained. The off-diagonal coefficients can effectively eliminate stray coupling in the calculation of **B** and **H** vectors. Some magnetic compensation problems, caused by the misalignment angle between the sensing coil and the excitation field in the 3-D tester, were also solved by means of rotational transformation of coordinates in calibration [3]. In addition, some typical magnetic properties of a cubic SMC specimen (SOMALOY™ 500) were measured and analyzed using the calibrated novel sensing structure.

II. IMPROVEMENT OF THE SENSING STRUCTURE

The improved sensing structure combines three pairs of minimized *H* coils and corresponding *B* coils, as shown in Fig. 1. Each *H* sensing coil is wound around a 0.5 mm thickness epoxy resin board with 200 turns. A thin (0.4 mm thickness) and round *B* coil is embedded in the central hole of the epoxy resin board. The winding terminals are twisted to eliminate electromotive force (EMF) induced by unwanted stray field. Six such *B-H* combined coils form a cubic sensing box with internal size of 22 × 22× 22 mm^3. A cubic SMC specimen with 22 mm side length is cut and loaded into the box. As a result, surface of the specimen is as close as possible to the *B-H* sensing coils.

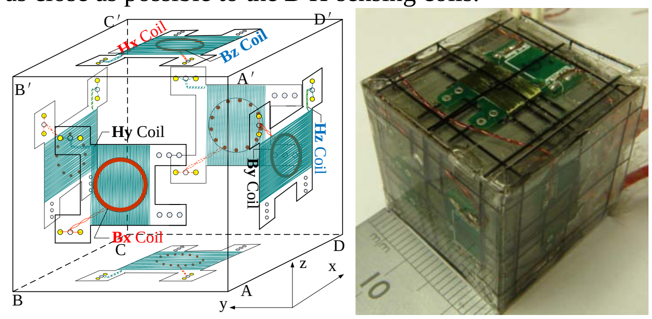

Fig. 1. Improved *B-H* sensing structure: (a) schematic structure; (b) product photo.

III. CALIBRATION OF THE SENSING COILS

The sensing coil coefficients in 3-D magnetic calculation should be a 3 × 3 matrix. The diagonal elements, which are the products of cross-section area and number of turns, can be obtained by calibrating in a long solenoid which can generate uniform field. The off-diagonal elements, which are the non-cross-sectional coefficients of the coils, can be calibrated in the 3-D tester by using the calibrated diagonal elements of the coefficients.

A. Calibration in solenoid and 3-D tester

The induced EMF of the sensing coils by alternating field is governed by *Faraday Induction Law*; therefore, the coil coefficient *K* can be obtained. Taking the H_x coil as an example, K_{Hxx}, K_{Hxy} and K_{Hxz}, are coefficients along *x*-, *y*- and *z*-axis, respectively. The configured sensing direction needs to be in accord with that of excitation structures. Fig. 2 shows the EMF signals of *B* and *H* sensing coils along three axes when the diagonal AC′ of the cubic sensing box as shown in Fig. 1, is in parallel with the generated field in solenoid. It can be seen that the EMF signals for H_x, H_y, H_z, B_x, B_y and B_z are good sinusoidal waveforms, and have no phase difference. The phase angle between the EMF signals and the excitation current is exactly 90 degree.

By using the calibrated diagonal coefficients, we can calculate the alternating magnetization in 3-D tester and calibrate the off-diagonal coefficients simultaneously. For example, K_{Hxy} and K_{Hxz} of H_x coil can be calculated by means of K_{Byy} and K_{Bzz}, respectively. The value of off-diagonal coefficient is positive or not depends on the phase difference. 0 degree is corresponding to positive value and 180 degree is corresponding to negative value. Table I is the calibrated coefficients of the *H* sensing coils.

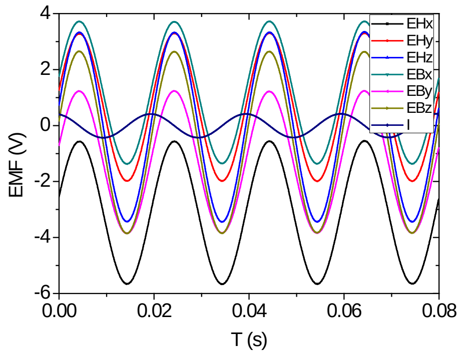

Fig. 2. EMF signals of B and H sensing coils along three axes when the excitation current is given.

TABLE I
Coefficients of the H Sensing Coils (unit: M^2)

K_{Hxx}	K_{Hxy}	K_{Hxz}
2.600×10^{-3}	-1.239×10^{-6}	-3.126×10^{-5}
K_{Hyx}	K_{Hyy}	K_{Hyz}
1.237×10^{-5}	2.747×10^{-3}	-1.782×10^{-6}
K_{Hzx}	K_{Hzy}	K_{Hzz}
-6.059×10^{-7}	1.992×10^{-5}	2.738×10^{-3}

B. Expressions of B and H in 3-D tester

The calibrated coefficients are used to calculate **B** and **H** vectors of the specimen magnetized in the 3-D tester. The off-diagonal coefficients for B coils can be ignored since the B signals are well controlled and the small off-diagonal coefficients contribute very little. Hence, the **B** vector can be simply calculated from:

$$U_{Bi} = K_{Bii}\frac{\mathrm{d}B}{\mathrm{d}t} \qquad (i = x, y, z)\cdot \tag{1}$$

However, for H coils, the off-diagonal elements must be concerned to eliminate the unwanted stray coupling field. The inducted voltages crossing H coils can be expressed as

$$\begin{cases} U_{Hx} = \mu_0\left(K_{Hxx}\dfrac{\mathrm{d}H_x}{\mathrm{d}t} + K_{Hxy}\dfrac{\mathrm{d}H_y}{\mathrm{d}t} + \dfrac{K_{Hxz}}{\mu_0}\dfrac{\mathrm{d}B_z}{\mathrm{d}t}\right) \\ U_{Hy} = \mu_0\left(\dfrac{K_{Hyx}}{\mu_0}\dfrac{\mathrm{d}B_x}{\mathrm{d}t} + K_{Hyy}\dfrac{\mathrm{d}H_y}{\mathrm{d}t} + K_{Hyz}\dfrac{\mathrm{d}H_z}{\mathrm{d}t}\right) \\ U_{Hz} = \mu_0\left(K_{Hzx}\dfrac{\mathrm{d}H_x}{\mathrm{d}t} + \dfrac{K_{Hzy}}{\mu_0}\dfrac{\mathrm{d}B_y}{\mathrm{d}t} + K_{Hzz}\dfrac{\mathrm{d}H_z}{\mathrm{d}t}\right) \end{cases} \tag{2}$$

Then, the expressions of **B** and **H** can be obtained.

C. Compensation of the sensing coil

The measured **B** and **H** may have deviations if the coordinate axis of the sensing structure is misaligned with that of the excitation structure. This error can be corrected by means of the rotational transformation of coordinates.

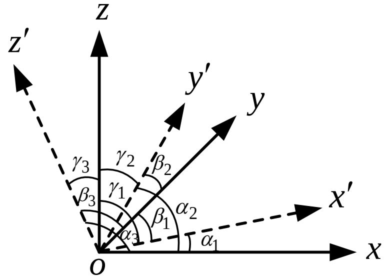

Fig. 3. Rotation of coordinates.

Fig. 3 illustrates the rotation of coordinates in three dimensions where x, y, and z, are three orthogonal coordinate axes of the 3-D testing system. x', y', and z' are misaligned axes of the sensing structure. The angles between x' axis and x, y and z axes are denoted as α_1, β_1 and γ_1, respectively. Similarly, the angles between y' and x, y, z, and z' and x, y, z are α_2, β_2, γ_2, and α_3, β_3, γ_3, respectively.

$$\begin{bmatrix} H_x' \\ H_y' \\ H_z' \end{bmatrix} = \begin{bmatrix} \cos\alpha_1 & \cos\beta_1 & \cos\gamma_1 \\ \cos\alpha_2 & \cos\beta_2 & \cos\gamma_2 \\ \cos\alpha_3 & \cos\beta_3 & \cos\gamma_3 \end{bmatrix} \begin{bmatrix} H_x \\ H_y \\ H_z \end{bmatrix} \tag{3}$$

where H_x', H_y', H_z' are the measured component values of the magnetic field strength, and H_x, H_y, and H_z the true values of magnetic field strength.

IV. EXPERIMENTAL RESULTS

Fig. 4 illustrates a series of well-controlled round and elliptical **B** loci and corresponding **H** loci at 20 Hz in the *yoz*-plane. It can be seen that **H** loci lie in the plane same as that of **B** loci. **H** loci change from elliptical shape to quadrangular shape when **B** loci are circles, while **H** loci are saddle-like shapes when the **B** loci are ellipses. These show that the rotational hysteresis features depend strongly on the magnetized process. Slightly anisotropy is also found out that y-axis is easy to be magnetized. More detailed analysis will be presented in full paper.

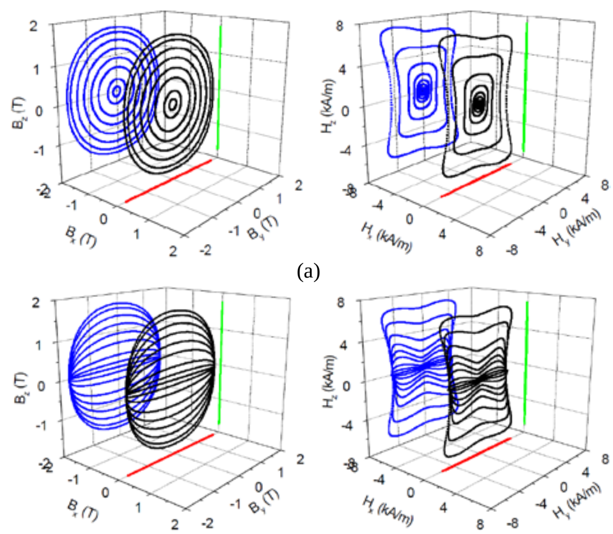

Fig. 4. **B** loci (left), and corresponding **H** loci (right), and projections in *yoz*-plane at 20Hz: (a) round **B** loci and corresponding **H**; (b) ellipitcal **B** loci (y is the majior axis) and corresponding **H** loci.

V. REFERENCES

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