Journal of Korean Magnetics Society, Volume 5, Number 5, October 1995

CALIBRATION OF A NEW CAPACITIVE TORQUE SENSOR FOR MEASURING BASIC MAGNETIC CHARACTERISTICS WITH ELECTROMAGNETIC AND GRAVITATIONAL FORCES

M.Y.Kim, K.L.Choi, S.J.Choi, E.Y.Song, Y.H.Lee[*] and J.R.Rhee
Department of physics Sookmyung Women's University, Seoul 140-742, Korea
[*]Department of physics Jeonbuk National University, Jeonju 560-756, Korea

Abstract - **With a newly designed capacitive torque sensor a multipurpose magnetometer for measuring basic magnetic characteristics such as hyteresis loops, magnetic anisotropy and magnetostriction was built. In order to calibrate the capacitive torque sensor, we measured the output voltages of the sensor by applying the torques due to the electromagnetic and gravitational forces. Experimental results of the several calibration method for the capacitive torque sensor showed good agreement within 3 %.**

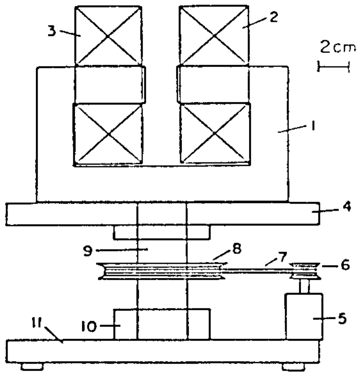
I. INTRODUCTION

We have already reported a newly designed multipurpose magnetometer[1] which is based on the fact that most magnetic characteristics could be obtained by analyzing the torque acting on a sample under appropriate magnetic field. This multipurpose magnetometer consists of a miniaturized rotatable electomagnet with power supply, three capacitive sensors for measuring hysteresis loops, magnetic anisotropy and magnetostriction of thin film and bulk samples, and a transformer-ratio-arm (TRA) bridge for detecting a small capacitance change of the sensor with high resolution. We report here several calibration methods for this system with known gravitational, electrostatic, magnetoanisotropic and electromagnetic torques.

II. MEASUREMENT SYSTEM AND CALIBRATION

A. Outlines of the Measurement System

A small electromagnet (10 Kg weight, 23 mm air gap) produces 6 KOe of field H by 350 W power consumption. Such miniaturization is realized by eliminating the cooling system since the duration of magnet excitation is limited only to the measuring process (about 4 s). The miniaturized rotatable electromagnet is shown in Fig. 1.



1 : Yoke 2,3 : Magnetizing coil 4 : Supporting disc 5 : Driving motor 6,8 : Pullies for driving the supporting disc 7 : Rubber belt 9 : Shaft 10 : Bearing

Fig. 1. Miniaturized rotatable electromagnet.

The structure of the capacitive torque sensor is shown in Fig. 2. Four pieces of phosphor-bronze plate (width w, length l and thickness t) form a cross beam, which is vertically suspended at its upper end. The torque generated on the sample attached at the lower end twists the cross beam by an angle ϕ. This ϕ causes capacitance change ΔC of the two parallel-plate capacitors (with total capacitance C_0) attached to the lower end of the cross beam with average distance r from the beam axis. For torques, the angle ϕ can be written as $\phi = K\tau$ with the system constant K so that one gets

$$\Delta C/C_0 = -(Kr'/g_a)\,\tau\,, \tag{1}$$

where g_a is the air gap of the capacitor, r' is half the length of the movable electrode plate. This capacitance change can [illegible] ured by the TRA bridge of Fig. 3. The [illegible] age V_0 of the TRA bridge is calculated [illegible] conductance) to be

$$V_0 = -nKr' \; [illegible] \; \tau \; [illegible] \tag{2}$$

where G and [illegible] are gain of the lock-in amplifier and total voltage of the secondary coil, respectively.

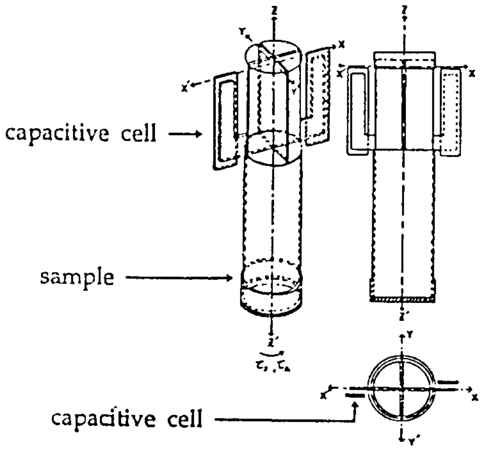


Fig. 2. Capacitive torque sensor.

B. Calibration

1) Gravitational Method

When the normal of the movable electrode declined by angle α to the horizontal direction, the torque $\tau_G = mgr \sin\alpha$ is generated to the cross beam axis and the torque sensor's capacitance changes. Then the gravitational system constant K_G can be calculated as

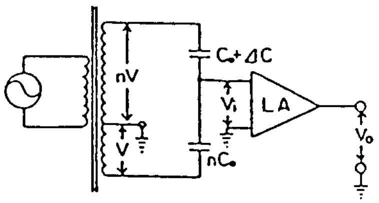


Fig. 3. Transformer-ratio-arm bridge.

$$K_G = (n+1)\,\varepsilon_0 A V_0 \,/\, nGVr'\, mgr\alpha\, C_0\,, \tag{3}$$

where ε_0 is the permittivity of the free space, mg and A are the weight and the area of the sensor's movable electrode, respectively.

2) Electrostatic Method

Another known torque is generated by applying DC bias[2] V_{DC} to the electrode of the capacitive torque sensor. In this case the system constant K_E is obtained to be

$$K_E = 2(n+1)\,\varepsilon_0^2 A^2 V_0 \,/\, nGrr'\, V_{DC}^2 V C_0^3. \tag{4}$$

3) Magnetic Anisotropy Method

For the magnetically shape anisotropic sample, the torque $\tau_A(\theta)$ is produced on the sample under the rotating magnetic field $H(\theta)$, θ being the azimuthal angle of H field. The system constant K_A for the torque $\tau_A(\theta)$ is expressed to be

$$K_A = (n+1)\,\varepsilon_0 A V_0 \,/\, nGVr'\, J_s v H \sin(\theta-\psi)\, C_0\,, \tag{5}$$

where ψ is the angle between the saturation magnetization J_s and the easy magnetization axis and v is the volume of the sample.

4) Electromagnetic Torque Method

For measuring magnetization J of the sample (thin film or needle shape, volume v), an added field H_a perpendicular both to $H(\theta)$ and to the easy magnetization axis needs to be produced by an auxiliary small Helmholtz coil. A torque τ_M (= vJH_a) is then produced on the sample. The system constant K_M for this torque is expressed to be

$$K_M = (n+1)\ \varepsilon_0 A V_0 \,/\, nGVr'\ j_s v H_a C_0 \ . \qquad (6)$$

III. EXPERIMENT AND RESULTS

When the normal of the sensor's electrode is declined to the horizontal direction by small angle ±3.27° , the peak to peak output voltage V_0 = 5.50 V of the TRA bridge by the weight of sensor's electrode is shown in Fig. 4. For the experimental parameters, l = 30.0, r = 8.0, r' = 3.0, t = 0.10, g_a = 0.20, and w = 6.0 in mm, n = 500, G = 400, V = 0.30 V, the system constant K_G is obtained to be 760/J and the τ_G (= $mgr \sin\alpha$) was 1.75 μJ.

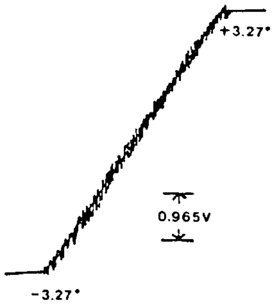


Fig. 4. Output voltage V_0 of TRA bridge as a function of the angle between normal of the sensor's electrode and horizontal direction.

In order to determine the system constant K_E, DC bias V_{DC} was applied to the capacitive torque sensor. It was found that the output voltage V_0 of the lock-in amplifier was proportional to V_{DC}^2 as shown in Fig. 5. The results agreed with the theoretical expression of Eq. (4). The system constant K_E is obtained to be 715/J and electrostatic torque τ_E (= $rC_0V_{DC}^2/2g_a$) was 1.42 μJ with V_{DC} = 94.5 V and V_0 = 826 mV. When we raise the gain G to easily obtainable 10^4, the torque to produce output V_0 of 5 mV is 0.086 nJ.

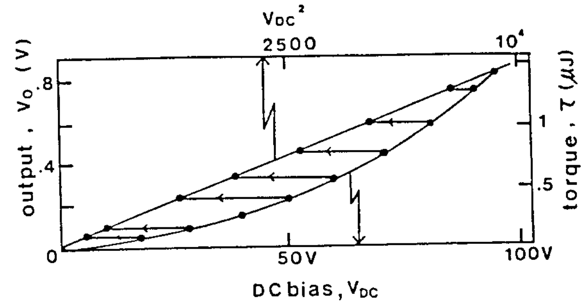


Fig. 5. Output voltage V_0 of the lock-in amplifier as a function of DC bias V_{DC}.

Fig. 6 shows the anisotropy torque curves of Ni wire (0.13 mm dia., 8.0 mm length) under the rotating magnetic field 80~400 Oe by the variation of the angle (± 180°) between applied magnetic field and easy magnetization axis. Calibrating measured data is carried out by measuring change of output voltage due to addition of an equivalent capacitance (0.02pF) to the capacitive torque sensor. Then system constant K_A is obtained 733/J considering angle ψ = 7.2° between saturation magnetization and easy magnetization axis.

To get the system constant K_M, applying the perpendicular added field H_a = 14.4 Oe for measuring hysteresis loop under the magnetic field ± 650 Oe in easy magnetization direction of

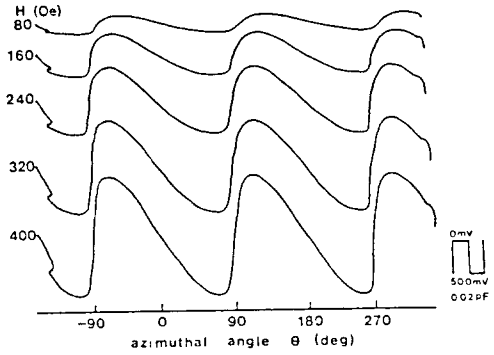


Fig. 6. Anisotropic torque curves of Ni wire sample (0.13 mm dia., 8.0 mm length). V_0 = 870 mV, τ_A = 217 nJ.

the sample, the obtained system constant K_M is 720/J with output voltage V_0 = 38.7 mV and coercive force H_c = 63 Oe. The hysteresis loop of Ni wire sample is shown in Fig. 7.

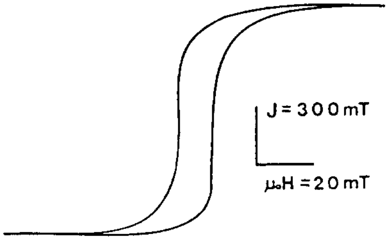


Fig. 7. Hysteresis loop of Ni wire sample (0.13 mm dia., 8.0 mm length).

Ⅳ. CONCLUSION

With electromagnetic and gravitational forces the system constants for the new capacitive torque sensor of multipurpose magnetometer for basic magnetic characteristics are obtained to be K_G = 760/J, K_E = 715/J, K_A = 733/J, K_M = 720/J, respectively. These results show good agreement within 3 %. The resolution of the capacitive torque sensor we built is at worst 0.1 nJ with amplifier gain 10^4. Only a few milligrams of ferromagnetic samples are sufficient to get the hysteresis curve with the sensor.

REFERENCES

[1] Y.H.Lee, Y.D.Shin, K.H.Lee, M.Y.Kim, and J.R.Rhee, " A Multipurpose Magnetometer for Measuring Basic Magnetic Characteristics with a Newly Designed Capacitive Torque Sensor ", Proceedings of **INTERMAG** 95 in San Antonio, Texas, USA.

[2] Y.H.Lee, Y.D.Shin, B.H.Huh, K.H.Lee, H.J.Kim, S.H. Han, I.K.Kang, J.R.Rhee, " DC Biased Capacitance Method for Measuring Thin Film Magnetostriction and ΔE Effect ", IEEE Trans. **Mag.** **30(7)**, 4713-4716 (1994).