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A Versatile Toroid Hysteresis Loop Tracer with Direct Readout of Loop Parameters

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A versatile hysteresis loop tracer for toroidal samples has been constructed which allows loop parameters to be determined extremely rapidly. (1) The winding operation is eliminated for toroids with inside diameters greater than 1.5 cm. (2) The loop axes are calibrated directly in oersteds (horizontal) and gauss (vertical) by setting three Helipots to the toroid dimensions. (3) Direct Helipot dial readout of coercive force and remanent induction is possible.

INTRODUCTION

THE toroid hysteresis loop tracer is an extremely useful tool for the measurement of basic loop parameters of magnetic materials. Several descriptions of loop tracer systems have appeared in the technical literature.[1–3] The toroidal shape is convenient because there are no demagnetizing effects to modify the displayed loop. In addition, samples can be fabricated easily. There are, however, several disadvantages in utilizing toroidal samples. First, it is usually necessary to provide drive and sense windings on each individual toroid to be measured. Second, the loop calibration depends on the size of the windings and the toroid dimensions. It is necessary to use toroids with identical mechanical dimensions and windings with the same number of turns or, alternatively, to calibrate the hysteresis loop separately for each toroid. Finally, loop parameters must usually be determined by direct visual measurement of the displayed loop. A hysteresis loop tracer for toroids has been developed which avoids these difficulties and allows loop data to be obtained accurately and rapidly. The drive and sense windings have been incorporated into the sample holder so that it is not necessary to wind each toroid. A network of amplifiers in the drive and sense channels with gains controlled by Helipots set to the toroid dimensions allows the loop axes to be calibrated directly in oersteds (horizontal) and gauss (vertical). The use of a chopper modulated reference voltage technique[4] allows direct Helipot readout of the coercive force and remanent induction.

INSTRUMENTATION

A block diagram of the instrumentation is shown in Fig. 1. A triangular waveform at 100 Hz drives a power amplifier which can deliver 10 A to the toroid drive winding. Integration of the sense winding output is done with a conventional Miller integrator. A filter in the operational amplifier feedback loop limits integration to signal components above 1 Hz so that dc integrator drift problems are avoided. The above components are rather conventional and will not be discussed further. The improvements on the earlier designs involve the remaining components: the sample jig, the horizontal and vertical axis calibration networks, and the chopper reference scheme for digital readout of the coercive force and remanent induction.

The sample test jig is shown in Fig. 2. The photograph shows the jig with the top section removed and a ferrite toroid in place over the left hand pedestal. The two

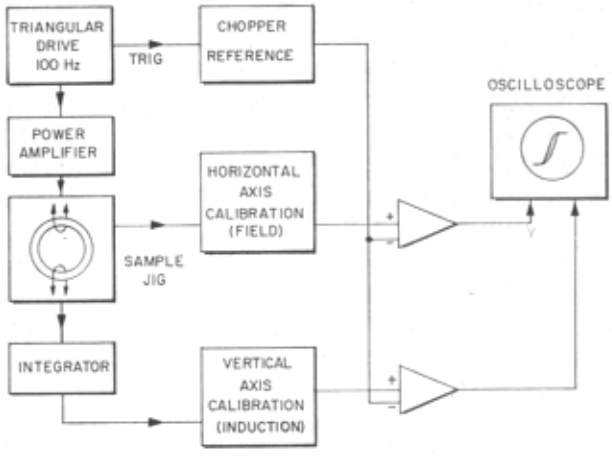

FIG. 1. Block diagram of the toroid hysteresis loop tracer system.

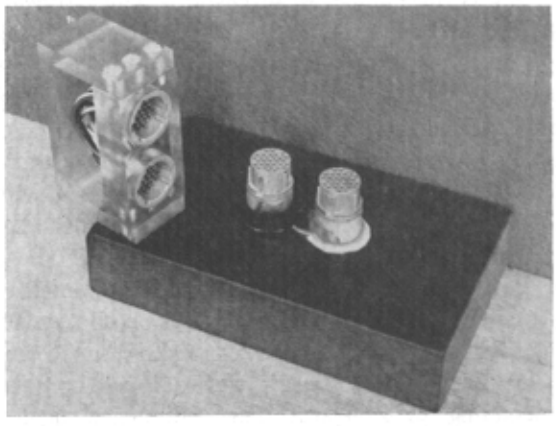

FIG. 2. Sample holder for the toroid loop tracer.

[1] P. F. Elarde, Western Elec. Engr. **9**, 8 (1965).
[2] D. J. Grover, J. Sci. Instrum. **43**, 718 (1966).
[3] K. Hermann, Instrum. Control Systems **40**, 110 (1967).
[4] J. A. Weiss, Technical Note No. 1968-27, Lincoln Lab., MIT, Lexington, Massachusetts, 24 July 1968.

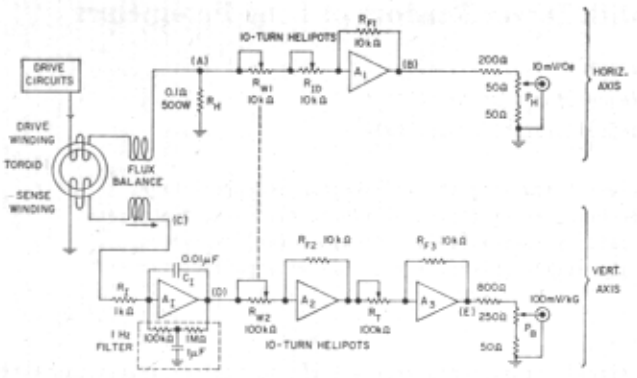

FIG. 3. Horizontal and vertical axis calibration electronics for the toroid loop tracer. A_1, A_2, A_3—Analog Devices 108C operational amplifiers; A_I—Dymec 2460A operational amplifier.

pedestals consist of Amphenol series 222 31-contact plugs which have been machined to 1.59 cm o.d. The pieces are epoxy bonded to Lucite sleeves which are mounted on the Bakelite baseplate. Mating connectors are positioned in the Lucite top section. The connectors are wired so that 15-turn drive and sense windings thread the toroid when the sample and top section are in place. The unit has good mechanical strength and can withstand the repeated removal and replacement of the top section which is necessary during routine measurements.

A wiring diagram of the horizontal and vertical axis calibration networks is shown in Fig. 3. The horizontal or field-axis circuit produces an output voltage which is directly proportional to the magnetic field in the toroid and is independent of the toroid dimensions. Ampere's law was used to relate the current I in the drive winding to the field H by assuming a uniform circumferential field around a circular path at the center of the toroid cross section with a diameter $D_{av}=$ (o.d.+i.d.)/2.

$$I(A)=\frac{2.5D_{av}(\text{cm})\cdot H(\text{Oe})}{N_H(\text{turns})}. \tag{1}$$

Here, N_H is the number of drive turns which thread the toroid. The return path for the drive current is through the 0.1 Ω 500 W resistor R_H to ground so that the voltage at point (A) is simply IR_H. For a fixed H this voltage is linearly proportional to D_{av}. A field calibration which is independent of D_{av} is obtained by means of operational amplifier A_1 with a fixed feedback resistor R_{F1} and an input resistance controlled by Helipots set to the toroid i.d. and width $W=(o.d.-i.d.)/2$, respectively. The gain from (A) to (B) is $R_{F1}/(R_{id}+R_{W1})$. The values of R_{id} and R_{W1} are determined by the dial settings on 10-turn 10 kΩ digital Helipots. The dials are set to the inside diameter D_{id} and width of the toroid W, with full scale or 10 turns corresponding to 2.54 cm. This calibration facilitates setting the digital readout Helipot dials directly from toroid dimensions read off calipers calibrated in English units. The output voltage at point (B) per unit field in the toroid is given by

$$[6.35\cdot R_H(\Omega)/N_H(\text{turns})](\text{V/Oe}), \tag{2}$$

independent of the toroid dimensions. With $R_H=0.1$ Ω and $N_H=15$ turns, Eq. (2) yields 42.35 mV/Oe. Adjustment of P_H allows the channel to be set for 10 mV/Oe horizontal output, which is convenient for a calibrated oscilloscope display.

The vertical channel circuit is shown in the lower part of Fig. 3. It produces a voltage which is proportional to the average circumferential magnetization in the toroid and independent of the toroid dimensions. Auxiliary coils are required to balance out air flux. This flux balance arrangement consists of a stationary drive coil concentric with a movable sense coil. The coil position is adjusted for zero integrator output at moderate drive current and no toroid on the test jig. Integration is done with a conventional Miller integrator circuit utilizing a low noise low drift operational amplifier A_I. The 1 Hz filter eliminates dc integrator drift problems. From Faraday's law, the voltage at point (C) is related to the time rate of change in the average circumferential magnetic induction B by

$$E_s(\text{V})=10^{-8}\cdot N_s(\text{turns})\cdot T(\text{cm})\cdot W(\text{cm})\cdot dB/dt(\text{G/sec}), \tag{3}$$

where N_s is the number of turns on the sense winding and T is the toroid thickness. A rectangular cross section is assumed. The change in voltage at (D), ΔE_I, due to a change in the average circumferential induction ΔB is given by

$$\Delta E_I(\text{V})=[10^{-2}\cdot N_s(\text{turns})\cdot T(\text{cm})\cdot W(\text{cm})\cdot \Delta B(\text{kG})]/[R_I(\text{k}\Omega)\cdot C_I(\mu\text{F})], \tag{4}$$

where R_I is the input resistance and C_I the feedback capacitance for amplifier A_I. This voltage is proportional to the product of T and W. An output at (E) which is independent of T and W is obtained by means of amplifiers A_2 and A_3, in an arrangement similar to that for the horizontal channel. The values of R_{W2} and R_T are controlled by dial settings on 10-turn 100 kΩ digital Helipots. Full scale (10 turns) corresponds to 2.54 cm (1 in.). The Helipot which determines R_{W2} is ganged on the same shaft with the R_{W1} Helipot for the horizontal channel. With the dials set at W and T, the output voltage at (E) per unit change in induction is

$$[6.45\times10^{-4}\cdot N_s(\text{turns})]/[R_I(\text{k}\Omega)\cdot C_I(\mu\text{F})](\text{V/kG}), \tag{5}$$

independent of the toroid dimensions. With $N_S=15$ turns, $R_I=1$ kΩ, and $C_I=10^{-2}$ μF, the calibration is about 970 mV/kG. Adjustment of P_B allows the channel output to be set for 100 mV/kG.

The chopper-modulated reference voltage technique for the accurate determination of hysteresis loop parameters has been described in detail by Weiss in conjunction with a different type of loop tracer.[4] In the present system the technique was applied to the measurement of the remanent induction B_r and the coercive force H_c. For B_r, a calibrated bias voltage is applied to the vertical axis of the oscilloscope display on alternate cycles so that two loop images, one above the other, are visible. The bias required to make the two loops tangent is equal to the separation of the two remanence points on a single loop. The bias voltage amplitude is controlled by a 10-turn Helipot calibrated at 200 mV/turn so that the dial reading when the loops were tangent corresponds to B_r in kilogauss (1.0 kG/turn). The procedure is similar for the H_c measurement except that the calibration was 20 mV/turn. The bias is applied to the field (horizontal) axis on alternate cycles and the two loops are displaced horizontally. The Helipot setting when opposite sides of the two loops crossed symmetrically is the coercive force (1.0 Oe/turn). Digital readout Helipots were used. After the proper adjustments are made, the loop parameters are simply read off the dials. The entire procedure can be carried out in less than 1 min.

CALIBRATION

Calibration was accomplished using a precision current source and a precision voltmeter. The Helipots were set for $W=0.254$ cm (0.1 in.), $D=2.386$ cm (0.9 in.), and $T=0.254$ cm (0.1 in.) so that the gain in each amplifier channel was unity. These parameters also represent typical values for toroids used with the apparatus. The horizontal axis was calibrated by adjusting the dc current through R_H to correspond to 1 Oe from Eq. (1) and then adjusting P_H for an output voltage of 10 mV. The vertical axis was calibrated by adjusting the voltage at point (D) to correspond to $\Delta B=1$ kG from Eq. (5) and then adjusting P_B for an output voltage of 100 mV. Accuracy is about $\pm 2\%$ for both axes.

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