Apparatus for the automatic plotting of magnetic hysteresis loops

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Abstract A versatile and simple instrument for automatically measuring the magnetic characteristics of materials is described. The instrument is highly stable and sensitive, making it suitable for plotting the Rayleigh loops of samples weighing less than 1 g. Another useful design characteristic is the automatic plotting of some magnetic parameters as functions of secondary variables, for example, the dependence on temperature of the remanent magnetic flux.

1 Introduction

The plotting of hysteresis loops is important in the study of magnetic materials. Different methods and instruments have been described for this purpose, for example the ballistic method; however most of them are time consuming. Other methods having a very fast display are of low precision, for example the dynamic method using an oscilloscope (Patton 1969, Fay 1972, Katz 1959). Finally, methods that use an XY recorder to give the display have, in many cases, difficulty with the drift of the DC component, the solution to this problem being tedious and expensive (Cioffi 1950, Mazzetti and Soardo 1966, Grover 1966, Scholes 1968, Lenaerts and Vanwormhoudt 1972).

This paper presents an inexpensive instrument of simple construction that combines the advantages of both the ballistic and the dynamic methods. It incorporates the accuracy of the former with the rapid operation of the latter. One added advantage is the automatic recording of any given parameter (e.g. coercitivity, saturation and remanent flux density) derived from the hysteresis loop as a function of a secondary variable such as temperature.

2 Basic concepts

The instrument described here is similar to the one described by Koppelmann (Storm 1955) except that it has the following important variations.

(i) The integration is made over the voltage signals instead of over the current flowing through the coils.

(ii) It allows automatic recording instead of point-by-point data acquisition.

(iii) It does not require a mechanical set-up since it is electronically constructed.

All these advantages, plus the fact that no previous calibration is necessary, converts it into a powerful tool for the study of magnetic materials. Figure 1 is the measuring circuit of the instrument. N_p and N_s are the number of turns on the primary and secondary coils, S the sample cross section, l the mean magnetic path length, M the mutual inductance of the air-cored transformer and e_b and e_h are the instantaneous voltages on the coils.

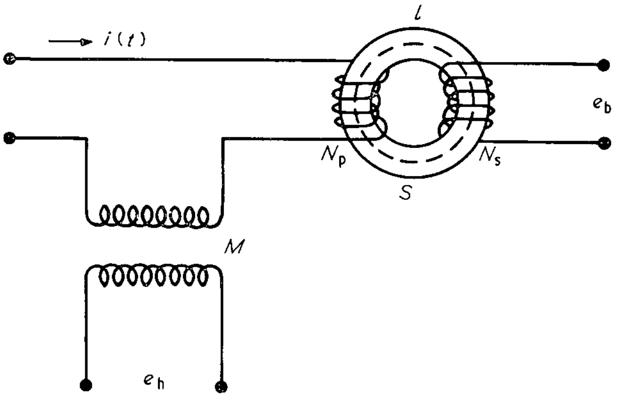

Figure 1 Schematic diagram of the sample circuit

The mathematical treatment is based on the idea that if a periodic function satisfies the following conditions.

(i) $Y(t_1+nT)=-Y(t_1-\frac{1}{2}T+nT)$, that is $Y(t)$ has no constant or even-order harmonic terms where n is the number of periods.

(ii) The time derivative $\mathrm{d}Y/\mathrm{d}t$ is made artificially equal to zero (chopped without affecting $Y(t)$) outside the time intervals $(t_1-\frac{1}{2}T+nT)$ and (t_1+nT).

Then it follows that

$$\frac{1}{T}\int_0^T \frac{\mathrm{d}Y(t)}{\mathrm{d}t}\,\mathrm{d}t=\frac{1}{T}\int_{t_1-T/2}^{t_1} \frac{\mathrm{d}Y(t)}{\mathrm{d}t}\,\mathrm{d}t=\frac{2}{T}\,Y(t_1). \tag{1}$$

From equation (1) it can be seen that the integral of $\mathrm{d}Y/\mathrm{d}t$ over a full period is proportional to the value of $Y(t)$ at a given time t_1.

If the magnetic excitation and detection systems are designed so that the magnetic field H and induction B satisfy the conditions for Y and $\mathrm{d}Y/\mathrm{d}t$, then it is possible to plot the instantaneous values of $B(t)$ and $H(t)$ on a XY recorder taking the time t_1 as a parameter. This can be done by a mechanical set-up (Storm 1955) which requires a point-by-point data acquisition. An automatic instrument which allows a continuous recording of the hysteresis loop is described in this paper.

3 Instrumentation

The magnetic field strength $H(t)$ and the flux density $B(t)$ satisfy condition (i). Replacing $\mathrm{d}Y(t)/\mathrm{d}t$ of equation (1) by e_b and e_h (related to the H and B time derivatives as seen in figure 1), we have

$$E_h=\frac{1}{T}\int_0^T e_h\,\mathrm{d}t=\frac{1}{T}\int_0^T \frac{Ml}{N_p}\frac{\mathrm{d}H(t)}{\mathrm{d}t}\,\mathrm{d}t=\frac{2MlH(t_1)}{TN_p} \tag{2}$$

$$E_b=\frac{1}{T}\int_0^T e_b\,\mathrm{d}t=\frac{1}{T}\int_0^T N_sS\frac{\mathrm{d}B(t)}{\mathrm{d}t}\,\mathrm{d}t=\frac{2SN_sB(t_1)}{T}. \tag{3}$$

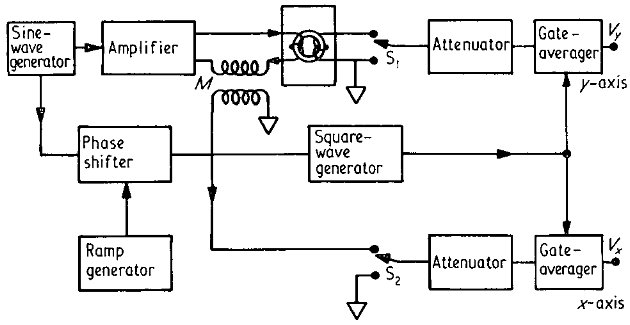

Figure 2 Block diagram of the instrument

E_h and E_b (H and B) are plotted using the instrument shown schematically in figure 2. The primary of the sample circuit is fed by an amplifier which can vary the maximum current. This allows the maximum magnetic field H to be matched with the sample's dimensions and magnetic characteristics. The e_h and e_b signals are processed simultaneously through two symmetrical circuits. The attenuator is optional, being used for large samples.

The gate-averager block, shown in figure 3, imposes condition (ii) on the time derivatives of B and H (i.e. $\mathrm{d}H/\mathrm{d}t$ and $\mathrm{d}B/\mathrm{d}t$ equal zero over the half period between $t=t_1$ and $t=t_1+\frac{1}{2}T$) and carries out the integration in equation (1). At stationary working conditions, the voltage gain of the gate-averager block is R_2/R_1 and then the plotter input voltages are

$$V_x=\frac{R_2}{R_1}\frac{2Ml}{TN_p}H(t_1) \tag{4}$$

$$V_y=\frac{R_2}{R_1}\frac{2SN_s}{T}B(t_1). \tag{5}$$

This shows that V_x and V_y are proportional to the values of H and B at time t_1 and this parameter is related point-by-point to the hysteresis loop. The proportionality constants can be easily and accurately evaluated, which means that no calibration is required. This is actually a coherent detection method and could be carried out with any standard lock-in amplifier type detector.

The blocking of the input signals during a time interval $\frac{1}{2}T$ (condition (ii)) is achieved by gates which are driven by a sine-wave squarer generator. The phase is controlled by a series of three variable phase shifters of constant amplitude. The angular shift given to the sine wave is related to the parameter t_1 through the angular frequency. The ramp generator, optically controlling the phase shifter by light-sensitive resistor devices, allows an automatic scanning of the

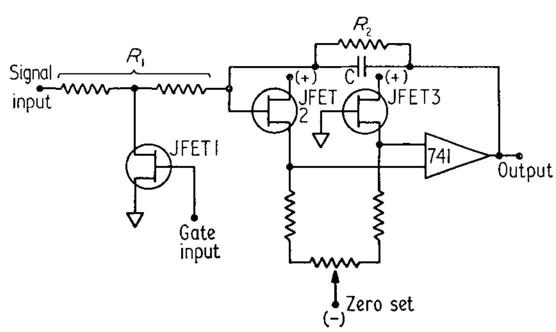

Figure 3 Gate-averager block circuit. JFETS are type 2N5458 or similar; JFET 1 was selected for its good off characteristics; JFET 2 and 3 are matched

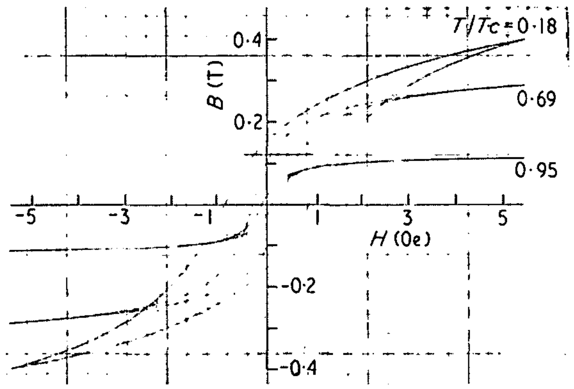

Figure 4 Family of hysteresis loops as a function of the reduced temperature for a Mn–Zn ferrite ring of 1 in mean diameter and ¼ in × ¼ in cross section. N_p and N_s 80 turns; operating frequency 74 Hz

magnetic hysteresis loop without any mechanical set-up. Thus a given point on the loop, or parameter related to it, can be studied as a function of a secondary variable (such as temperature) by simply setting a phase shift. Switches S_1 and S_2 are used in plotting the reference axes. One of the switches short-circuits the input of one channel while the loop is examined.

4 Operation and application to magnetic measurements

The following observations show the stability and reproducibility of the instrument.

(i) The hysteresis loop is perfectly closed for phase shifts greater than 360°.

(ii) Very good signal-to-noise ratios are obtained even with very small samples such as a soft ferrite toroid of 4 mm mean diameter and 1 mm² cross section. This sensitivity allows Rayleigh loops to be plotted which are needed to evaluate the coefficient of hysteresis loss with very low flux densities (IEC 1965).

(iii) The sample only needs a small number of turns.

The high frequency limit depends on the speed response of the particular electronic circuit. The lower limit is determined by the sensitivity and signal-to-noise ratio of the amplifiers. The maximum practical frequency is limited by the sample

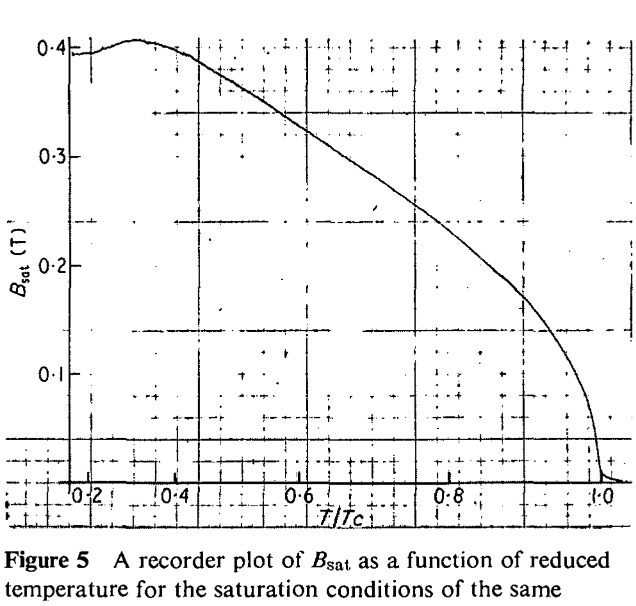

Figure 5 A recorder plot of B_{sat} as a function of reduced temperature for the saturation conditions of the same sample as in figure 4. *Tc* is the Curie temperature

circuit which is also the case with the dynamic method using an oscilloscope (Katz 1959).

A typical family of hysteresis loops as a function of temperature for a soft ferrite toroid is shown in figure 4. Phase shifts greater than 360° were used and no visible thickening of the recorder trace can be seen. Figure 5 is a plot of the saturation flux density against temperature for the same sample. It was obtained by fixing the phase shift angle for saturation conditions and then varying the sample temperature.

5 Conclusion

The instrument described in this paper is very versatile and easy to construct. Its sensitivity and accuracy make it suitable for many types of tests for a great variety of samples. The instrument has proved excellent in operation, tracing saturated hysteresis loops, Rayleigh loops and also saturation flux density, coercitivity and remanence curves as a function of secondary variables. The only limitation is that the loops must be symmetrical in order to satisfy condition (i) (§2) but this is usually the case, except for minor asymmetrical loops.

An important feature of this instrument is that no calibration is required prior to measurements, thus permitting the automatic tracing of the loops and reference axes.

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