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# HYSTERESIS-LOOP PLOTTER

*With this adapter the properties of magnetic materials can be displayed on a scope and evaluated for use as cores of chokes or transformers.*

WHEN designing or experimenting with transformers and inductors, it is useful to be able to determine magnetic characteristics of the laminations.

This hysteresis-loop plotter is a simple device that can be used with a low-frequency scope and a power supply with an output of 100 v. @ 25 ma. d.c., and 6.3 v. at 1 amp., a.c. Batteries may also be used instead of a power supply.

In spite of its simplicity, the loop plotter has many features, the most important of which are the following: (1). There is no need to specially prepare sample material as long as it has a  $\frac{1}{8}$ " diameter hole. (2). Only a few laminations are necessary to obtain reliable results. (3). The hysteresis loop can be displayed on the scope face as a motionless Lissajous figure and may be easily copied or photographed. (4). The device may be calibrated for absolute measurements of magnetic-iron characteristics if the flux of the test sample is considered equally distributed over the whole magnetic path. Toroid coils are particularly suited for such absolute hysteresis measurements.

## Principle of Operation

Refer to Fig. 1. In series with the primary of a one-turn transformer ( $T_2$ ) connected to a sinusoidal voltage  $e$  is a resistor,  $R$ , the voltage drop  $e_R$  across which is proportional to the magnetizing current  $i_m$ . This current produces in the laminations under test a magnetic flux that has an instantaneous value  $\phi$ . The flux,  $\phi$ , and the magnetizing current  $i_m$  are *not* proportional to each other; their relation is defined by what is called a "hysteresis loop."

Across the secondary of  $T_2$  will be a voltage  $e_o$  which is proportional to the instantaneous *rate of change* of the magnetic flux. It is beyond the scope of this article, but it can be shown mathematically that voltage  $e_o$ , when integrated, is proportional to the instantaneous value of the flux,  $\phi$ . In practical terms this means that  $e_o$  after integration is proportional to the instantaneous value of the magnetic flux in the iron. To produce a hysteresis loop on the screen of the scope, the input to the horizontal amplifier is the voltage drop across resistor  $R$ , horizontal deflection at any moment is proportional to the magnetizing current,  $i_m$ , and the vertical deflection is proportional to the instantaneous flux  $\phi$ , or induction.

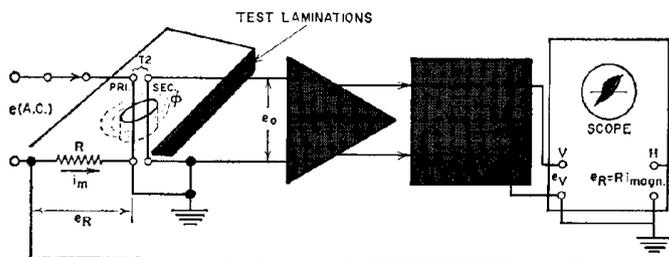
The integrator circuit ( $R10$  and  $C5$ ) is an  $RC$  network similar to a low-pass filter. There is an important condition that must be satisfied for the integrator to work properly. The capacitive reactance  $X_C$  of  $C5$  relative to the lowest input frequency must be no more than  $1/25$ th the value of the series resistor,  $R10$ . In this case  $R10$  is 270,000 ohms. The capacitive reactance at 60 cps should therefore be no more than 10,000 ohms which would be the reactance of a capacitor of approximately  $.25 \mu\text{f}$ . A  $1-\mu\text{f}$ . capacitor was chosen for the circuit to meet the requirement easily.

## Construction of Transformer $T_2$

The most complicated construction is transformer  $T_2$ , which is shown in Fig. 2. Its magnetic circuit is the test laminations into which it must be able to be inserted and removed. To accomplish this, both its primary and secondary "windings" are "one turn" only and consist of a thin copper tube which is the secondary and an insulated coaxial wire pulled through the tube, which is the primary. Both primary and secondary are passed through the mounting holes of the test laminations so that the magnetic flux is distributed in the laminations near the hole in concentric circles around the conductors as in Figs. 1 and 3. The copper tube is soldered into a banana jack and the center contact is wired to the top of the secondary of  $T_1$ .

The length of the copper tube should be approximately 2 to  $2\frac{1}{2}$  inches and its outside diameter  $\frac{1}{8}$ ". A stiff piece of 12-gauge copper wire approximately 3" long is then carefully covered with insulated sleeving. On the upper (right in the diagram) end of the wire, solder a small piece of copper

Fig. 1. A "transformer" ( $T_2$ ) with single turns samples the magnetic field in the core material and displays the loop.



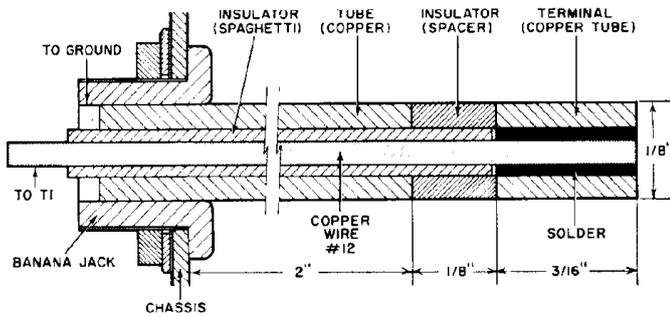


Fig. 2. Construction details for the sampling transformer.

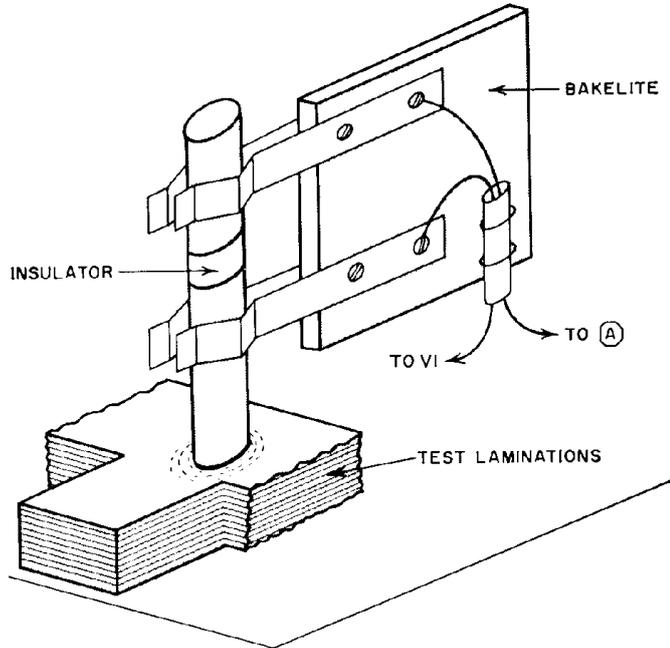


Fig. 3. Mounting of T2 and its insertion in test material.

tubing approximately 3/16" long. This will serve as a contact terminal and must be insulated from the larger copper tube by an insulating spacer of the same diameter as the tube 1/8" long and fitted over the insulated center wire. The prepared insulated inner wire is passed through the copper tube and adhered to it by means of a reliable adhesive (epoxy). After the adhesive hardens, the whole assembly should be sanded so its diameter will be uniform and the laminations will slide over it easily.

The magnetizing current is applied between the lower and upper contact of the inner wire. The induced secondary voltage appears between the lower end (ground) and the upper end (below the insulating spacer) of the exterior tube. The lower connections of both primary and secondary are permanently connected into the circuit in the banana jack. Contact to the upper part of the assembly is established by means of a removable clamp, with two pairs of contacts insulated from each other, and mounted on a small piece of Bakelite (see Fig. 3).

The complete schematic is shown in Fig. 4. The transformer that supplies the magnetizing current should be a small 50-v. transformer with a secondary voltage of at least 10 v. at 5 amp. (8 a. for short operation). The magnetizing current  $i_m$  can be adjusted to one of three values by connection through R3, R4, or R1. (You may use a tapped resistor instead of R3 and R4.) The current passes through the primary (inner wire of T2) and through R1. The voltage drop across R1 is applied to the horizontal input terminals of the scope. A 1- $\mu$ f. capacitor (C1) connects one side of the primary of T1 to ground.

The input to the amplifier is the output of T2. From the

plate of V1 to ground there is a 4000- $\mu$ f. capacitor (C2) which corrects for the phase shift between the horizontal and vertical outputs. The value of this capacitor must be determined by experiment so that the hysteresis loop is properly pointed on its extreme points and does not go over in small loops or have round corners. In Fig. 5A the loops in the end points are the result of undercompensation (C2 is too small). The loop (B) with the round corners and the larger area is caused by overcompensation (C2 is too large).

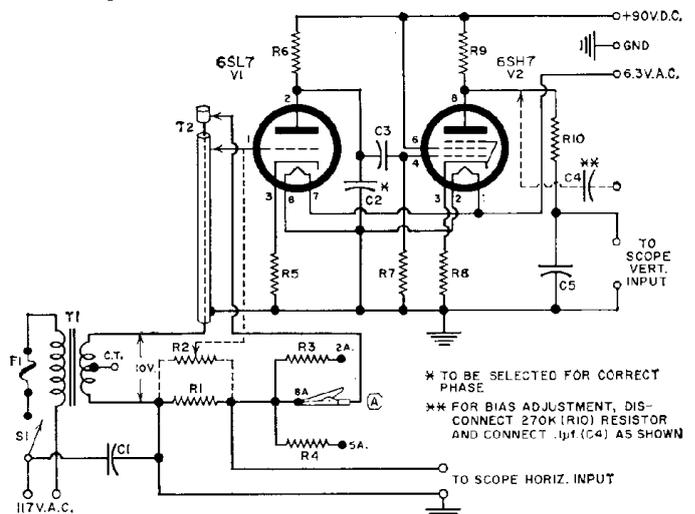
The high time constant of the coupling circuit (2  $\mu$ f. and 1.2 megohms) assures high gain at 60 cps. The value of cathode resistor R8 is somewhat critical and should be adjusted for a low-distortion output. The Lissajous of a distorted hysteresis loop is shown in Fig. 6A. There is a simple way to check if the hysteresis loop is free of distortion. Instead of taking the input to the amplifier from the secondary of T2, you can take a small fraction of the horizontal output voltage as shown by the dotted line to R2, and apply it to the grid of V1. In doing this the input to the amplifier will be a sinusoidal voltage and therefore the output before integration will also be sinusoidal. This voltage may be obtained by disconnecting R10 and connecting C4 to the plate of V2 and the output terminal to the scope vertical input.

The pattern obtained for approximately equal vertical and horizontal deviations should be a straight line. With increasing input voltage to the amplifier, the straight line will become curved at its extremes. To be able to determine the beginning deformation it is necessary to reduce the vertical gain of the scope. If the bias (value of R8) is correct, the deformation should begin simultaneously at both ends of the straight line. This means the bias setting has placed the operating point in the middle of V2's characteristic curve, between cut-off and saturation. To determine the correct value for R8 use a resistance decade. If a narrow ellipse appears instead of a straight line, there is phase shift between the vertical and horizontal outputs which can be corrected by changing the value of C2.

The integrated voltage across C5 may be fed directly to the input of the oscilloscope, if a blocking capacitor is incorporated in the instrument's input.

The following specifications, for the oscilloscope to be

Fig. 4. Circuit of the plotter amplifier, with scope outputs.



- R1—1 ohm, 20 w. res.
- R2—1000 ohm, 10 w. variable res.
- R3—6 ohm, 20 w. res.
- R4—4 ohm, 20 w. res.
- R5—1500 ohm, 1/2 w. res.
- R6—470,000 ohm, 1/2 w. res.
- R7—1.2 megohm, 1/2 w. res.
- R8—6800 ohm, 1/2 w. res.
- R9—100,000 ohm, 1/2 w. res.
- R10—270,000 ohm, 1/2 w. res.
- C1—1  $\mu$ f., 600 v. capacitor
- C2—4000  $\mu$ f., 400 v. capacitor (see text)
- C3—2  $\mu$ f., 400 v. capacitor
- C4—1  $\mu$ f., 400 v. capacitor (see text)
- C5—1  $\mu$ f., 400 v. capacitor
- T1—Power trans. pri: 117.; sec: 10 v. c.t. @ 10 amp. (Stancor P-6161 or equiv.)
- T2—See text
- S1—S.p.s.t. spring-loaded toggle switch
- F1—3 amp fuse
- V1—6SL7 tube, V2—6SH7 tube

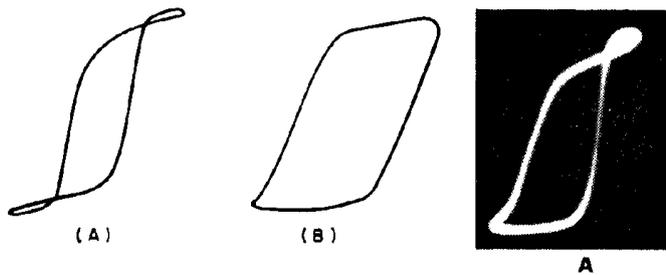


Fig. 5. Display is phased correctly by adjusting value of C2. (A) Under-compensation (C2 is too small). (B) Value of C2 has been overcompensated.

used in conjunction with the plotter, are not hard to meet: Vertical-channel a.c. input: approximately 30 mv./inch sensitivity.

Horizontal-channel sensitivity: 1 volt/inch.

Low-frequency limit: 5-10 cps for distortion-free and phase-correct amplification at 60 cps.

If the scope has a d.c. input, it should be used for the best frequency response. If the d.c. input is used, a large capacitor (2  $\mu$ f. with a 1- or 2-megohm resistor to ground) has to be connected between the plotter output and the scope input in order to keep the d.c. component of the output voltage from being applied to the scope input.

#### Construction

All components are mounted on a metal chassis 9 $\frac{1}{2}$ " x 4 $\frac{1}{2}$ " x 1 $\frac{1}{2}$ " as shown in Fig. 7. Transformer T2 is located on the left side of the chassis. Space for the largest sized test samples must be provided around T2. T1 is mounted to the right of the 20-watt resistors (R3 and R4).

These resistors become quite hot when the full current of 7-8 amperes (corresponding to 50-70 watts) passes through them. They must be located so that the heat will not affect other components. Full current should never be applied for longer than necessary since all component values are based on operation periods of 10-20 seconds. This is sufficient time for observing, tracing, or photographing the pattern. In order to avoid prolonged operation, the "on-off" switch is spring loaded so that it will automatically disconnect the transformer whenever it is released.

#### Using the Plotter

Connect the outputs of the plotter to the vertical and horizontal inputs of the scope and apply power. The laminations (a  $\frac{1}{8}$ " to  $\frac{3}{8}$ " stack is sufficient for a good pattern) which are to be tested should be carefully lowered over T2, and the connecting clamp put in place. Take care in setting the clamp to make sure that there isn't a short between the primary and secondary windings.

There is no fixed rule about the number of laminations to be used since the height of the curve depends not only on the section of the magnetic circuit but also on the quality of the alloy.

After putting the clamp in place, wait for 1-2 minutes for the capacitors to charge and for the spot on the scope to be centered. Next, apply the magnetizing current and note the pattern on the scope screen. Its width and height has to be set conveniently by means of the gain controls on the scope. The value of the magnetizing current determines the saturation condition of a specific magnetic alloy. For a given current, the quantity of laminations under test has no influence on the appearance of the hysteresis loop. A larger number of laminations increases only the total iron sections, and in the same proportion the total flux, without changing the distribution of the magnetic flux in the lamination itself. The increase in the total flux increases the secondary voltage of T2. After integration this voltage is proportional to the flux and causes the vertical deflection of the hysteresis loop. For

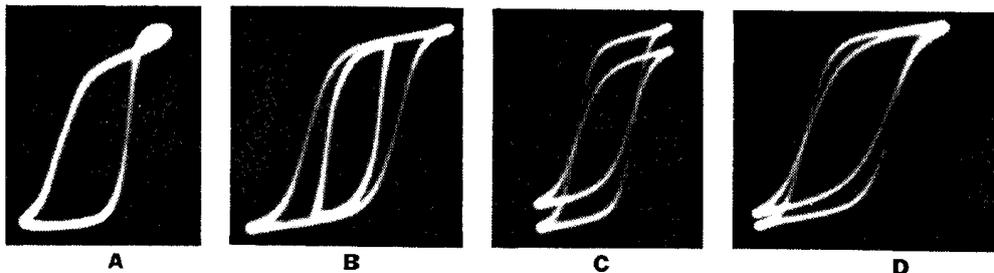


Fig. 6. (A) Display distorted by incorrect V2 bias. Adjust value of R2. (B) At saturation (larger loop) display spreads horizontally. (C) Another comparison of loops for two materials with different saturation points. (D) Loop enclosing larger area indicates greater iron losses. (B), (C), and (D) are double exposures.



Fig. 7. In layout, leave space for samples around T2 (left).

comparative measurements of permeability or reluctance, the thickness of the test samples must be the same. The value of the magnetizing current however determines the intensity of the magnetic flux in each lamination and therefore the flux at which saturation occurs.

In order to compare the quality of two types of iron in terms of their saturation point, the magnetizing current has to be increased for each type of lamination until the hysteresis loop goes over in an almost horizontal line. In Fig. 6B two hysteresis loops were photographed superimposed. The smaller, inner loop is for a 5-amp magnetizing current, the larger loop was made with a current of 8 amps. Saturation at 5 amps has not yet occurred, however at 8 amps, the curve is just beginning to go over in a straight line at its extreme points indicating that the magnetic circuit has become saturated. Since the horizontal deflection is proportional to the magnetizing current (voltage across R1) the length of the horizontal deflection at the moment saturation begins is a direct measure of the magnetomotive force and the field strength. The vertical deflection permits a determination of the amount of magnetic flux at that point at which saturation takes place.

It is well known that the slope of the hysteresis curve is a direct measure of the permeability of the alloy. The higher the permeability, the steeper the slope. In order to compare two samples of iron, the scope vertical and horizontal gain controls must be set so that a full hysteresis loop can be displayed on the screen without readjustment of the controls.

Two hysteresis loops of two different lamination samples having the same physical dimensions are shown in Fig. 6C. Both curves were made with the same current, therefore both samples were tested with the same magnetic potential. The smaller, less steep loop is that of iron with a lower saturation point and lower permeability. Notice that the widths of the two curves are identical.

The losses in the iron are determined by the area enclosed by the hysteresis loop. In contradistinction to the first measurements of saturation and permeability, the scope setting for the comparative measurements of the losses has to be

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made in such a way that the width and height of the hysteresis loops are the same in both cases. This is important since the determination of losses is a relative measurement in which loop area is considered in relation to the total loop height. The higher the losses, the greater is the ratio of the loop area to the loop height.

This example is shown in Fig. 6D where identical magnetizing currents were used but where the gain setting on the vertical input to the scope was adjusted so that the heights of the two hysteresis loops belonging to the different laminations became equal. The loop with the larger surface area corresponds to the lamination sample with the larger losses.

For further theory about magnetic circuits, the following references are suggested to the constructor:

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