Experiment A5. Hysteresis in Magnetic Materials

Objectives

This experiment illustrates energy losses in a transformer by using hysteresis curves. The difference betwen the B and H fields encountered in the lecture courses is illustrated. You will:

- use a hysteresis curve to measure the power loss of an iron core transformer
- for comparison, measure the loss for a ferrite core transformer
- estimate the curie point for ferrite.

Prework Questions.

1. Briefly explain what the physical meanings are of the three "magnetic" quantities (B, H, and M) mentioned in the Background.
2. How is the hysteresis curve related to the efficiency of a given transformer?
3. Draw what you expect the hysteresis curve in Fig. A5-3 would look like (paying attention to the position of the intercepts H_c and B_R) for (a) a larger amplitude and (b) a smaller amplitude of the AC current, with the temperature and frequency unchanged.

Topic 1. Magnetisation and Hysteresis Curves

Background

In the context of magnetic materials, *hysteresis* refers to the following phenomenon:

> When a piece of unmagnetised iron is placed in a solenoid which is carrying a current, the iron will become magnetised. If the current in the solenoid is then reduced to zero, the iron will remain partly magnetised. In order to demagnetise the iron, it is necessary to reverse the direction of current in the solenoid, but if the current in the reverse direction is increased further, the iron will magnetise in the reverse direction.
>
> A model made of small compass needles is available on a side bench to demonstrate these effects.

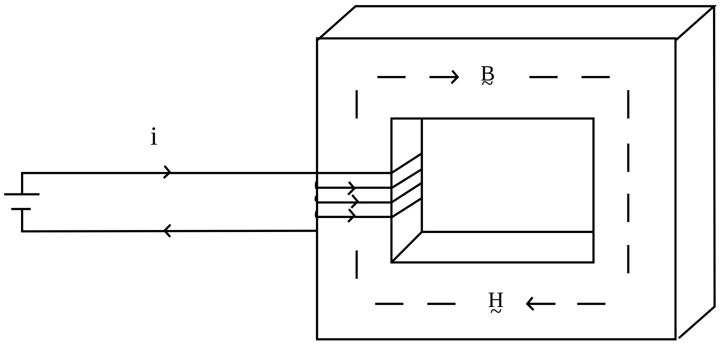

Fig. A5-1 **B** and **H** inside an iron core

To distinguish between (a) the total magnetic field in the iron (i.e., the field due to the solenoid plus the field due to the magnetisation of the iron), and (b) the part of the magnetic field created by the solenoid, it is useful to define two magnetic field quantities: one is the magnetic field, $\mathbf{B}$, the other is an auxiliary field $\mathbf{H}$. These quantities are often referred to simply as the '$\mathbf{B}$ field' and the '$\mathbf{H}$ field'.

If we wind a coil of N turns on an iron ring and pass a current i through the coil, then the value of H in the iron can be found from Ampere's law $\oint \mathbf{H} \cdot d\ell = Ni$, giving

$$H = Ni/\ell, \tag{1}$$

where ℓ is the length of the iron ring (i.e., the length of the dotted line in Fig. A5-1). The value of H is proportional to i and N but does *not* depend on the state of magnetisation of the iron.

The iron itself produces a magnetic field which depends on the degree of alignment of magnetic dipoles in the iron set up by orbital and spinning electrons. The degree of alignment can be specified by a quantity known as the magnetisation, $\mathbf{M}$.

In an unmagnetised piece of iron, $M = 0$, but the dipoles remain aligned over small regions in the iron known as magnetic domains. In an unmagnetised piece of iron, the domains are aligned in random directions. The effect of applying an H field is to align some of the domains to produce a non-zero value of M. The total magnetic field in the iron is

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}), \tag{2}$$

where μ_0 is the permeability of free space. Experimentally, we can measure B by winding a second coil on the iron core and measuring the emf induced in the coil when B changes with time.

As the current i in Fig. A5-1 increases from zero, the magnetisation M will increase from zero up to a certain value at which all the domains in the iron are perfectly aligned. Any further increase in i will have no effect on the value of M, and the iron is said to be saturated. A curve of the total field B vs. the applied field H as H increases from zero is called a *magnetisation curve*. A typical magnetisation curve for iron is given in Fig. A5-2.

Suppose we reach some arbitrary point (H_0, B_0) on the magnetisation curve shown (dotted) in Fig. A5-3. If we then decrease H to zero (by decreasing the current in the external coil), the iron will remain partly magnetised and there will be a 'residual field' B_R (see Fig. A5-3). By reversing the current, we can decrease B to zero at a value of H known as the 'coercive

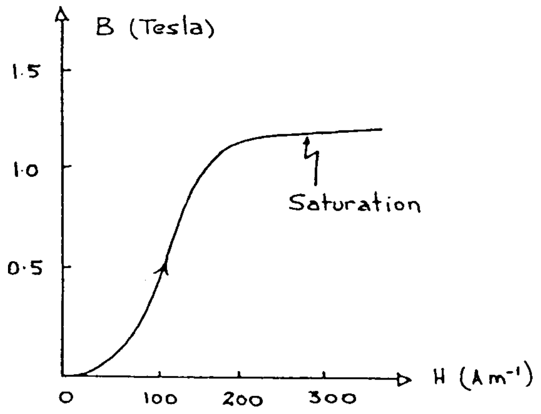

Fig. A5-2 Magnetisation curve

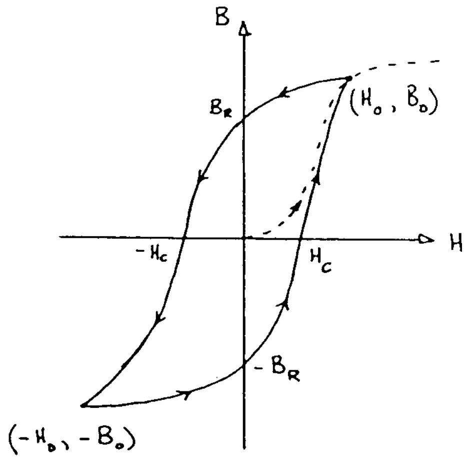

Fig. A5-3 Hysteresis curve

force', H_c. As H is made more negative, the iron magnetises in the reverse direction, and it will arrive at the point $(-H_0, -B_0)$ when the reverse current is equal in magnitude to the initial forward current. A curve of B vs. H for a complete cycle of increasing and decreasing current is known as a *hysteresis curve*. Various hysteresis curves are possible for a given specimen of iron, depending at which point on the magnetisation curve the hysteresis curve is started.

Apparatus

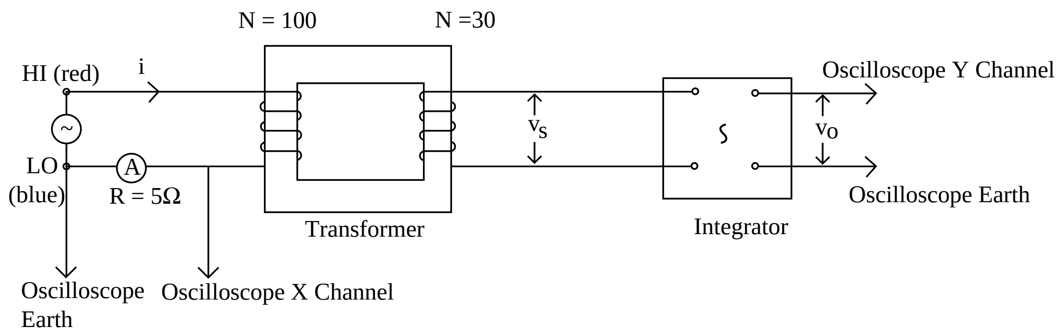

Fig. A5-4 Circuit used to display hysteresis curves

The circuit shown in Fig. A5-4 can be used to display the hysteresis curves of an iron core transformer directly on an oscilloscope screen. The transformer consists of a primary coil of $N_1 = 100$ turns and a secondary coil of $N_2 = 30$ turns, both wound on an iron core. A high power oscillator is used to produce an alternating current i in the primary coil. The H field in the iron is related to the current by eqn. (1). The current is indicated on a 'peak-reading' ammeter 'A', which indicates the *amplitude* of the current. The current amplitude can be varied by a gain control on the oscillator, and the alternating frequency can be varied from 1 Hz to 30 kHz.

The magnetic field B in the iron varies with time and induces a voltage

$$v_s = N_2 A\,(dB/dt) \tag{3}$$

in the secondary coil, where A is the cross-sectional area of the iron. Since we need to measure B rather than dB/dt, we will integrate the voltage v_s electronically. The basic principles of integrating circuits are described in the circuits and electronics notes. The battery operated integrator in Fig. A5-4 produces an output voltage v_o which is related to the input voltage v_s by

$$\begin{aligned} v_o &= \frac{1}{RC}\int v_s\,dt \\ &= \frac{N_2 A}{RC}\int \frac{dB}{dt}\,dt \\ &= \frac{N_2 A}{RC}B, \end{aligned} \tag{4}$$

where R and C are the resistance and capacitance, respectively, of the components used in the integrating circuit. The integrator provided has $R = 1\,\mathrm{M\Omega}$ and a gain control switch to select either $C = 0.01\,\mu\mathrm{F}$ or $C = 0.001\,\mu\mathrm{F}$. For uncertainty calculations, assume tolerances of 2% on R and C.

Both B and v_o will vary with time, but at all times

$$B = \frac{RC}{N_2 A}v_o. \tag{5}$$

The output signal from the integrator is connected to the Y input of an oscilloscope to produce a vertical deflection of the oscilloscope trace. The vertical deflection formed on the oscilloscope screen depends on the applied voltage v_o and on the VOLTS/CM setting on the oscilloscope, and is proportional to B.

The ammeter used to measure the primary current has a resistance of $R_A = 5.0\,\Omega$, so the voltage across the meter will be $R_A i$. This voltage signal can be applied to the X input of the oscilloscope to produce a *horizontal* deflection of the oscilloscope trace proportional to i, and therefore to H.

When conducting the experiment, take care not to let the current rise above about $1.2\,\mathrm{A}$ because the fuse in the ammeter will burn out.

The oscilloscope trace will therefore deflect vertically by an amount proportional to B and horizontally by an amount proportional to H. As the current in the primary coil alternates between positive and negative values, a hysteresis curve (B vs. H) on the oscilloscope screen will automatically be traced out.

Procedure

1. Connect the circuit shown in Fig. A5-4. In this experiment we will use an oscilloscope as an X–Y display to analyse the hysteresis curve. Set the coupling for each channel on the oscilloscope to DC. If your hysteresis curve appears 'backwards,' reverse the leads connecting the transformer to the integrator.

2. Set the gain control switch on the integrator to $C = 0.01\,\mu\mathrm{F}$ and obtain a hysteresis curve at an oscillator frequency $f = 50\,\mathrm{Hz}$. (If the curve on the oscilloscope display is highly distorted, then use the $C = 0.001\,\mu\mathrm{F}$ capacitor). Note that, as the amplitude

of the primary current increases, the hysteresis curves grow in size. The extreme tips of the curves lie on the magnetisation curve (Fig. A5-3). Record the coordinates (H_0, B_0) of the tips of the hysteresis curves for primary currents between 0.05 A and 1.0 A. The coordinates can initially be recorded in volts (corresponding to the Channel 1 and Channel 2 V/cm settings). Plot the magnetisation curve (B_0 vs. H_0) on a linear graph, after converting your measured values to B (Tesla) and H $(\mathrm{Amps} \cdot \mathrm{metres}^{-1})$ units using eqn. (1) and eqn. (5). The dimensions of the iron core are $\ell = 125\,\mathrm{mm}$ and $A = 19\,\mathrm{mm} \times 17.5\,\mathrm{mm}$, with uncertainties of $\pm 2\%$ in both ℓ and A.

C1 ▷

3. The ratio $B_0/\mu_0 H_0 = \mu_r$ for points along the magnetisation curve is called the relative permeability of the iron. For a vacuum, $B = \mu_0 H$ (since $M = 0$), so μ_r is the factor by which B is increased due to the presence of iron. Use your results to plot a graph of μ_r vs. H and compare your results with those given in the bench notes.

4. For current amplitudes $i = 0.1$ A and 1.0 A, make graphs of the hysteresis curves observed on the oscilloscope, labelling the axes carefully in B and H units. Curves such as these are used in studying the behaviour of transformers. The area of the hysteresis curve is important since it represents the work done in one hysteresis cycle per unit volume of iron. To prove this result, note that the current in the primary coil is $i = H\ell/N$ and the voltage across the primary coil is $v = N_1 A\,(dB/dt)$. Since the power used is $p = vi$, and the work done in a small time dt is $dW = p\,dt$, the total work done in one complete cycle is

$$\begin{aligned} W &= \oint p\,dt \\ &= \oint NA\frac{dB}{dt}\frac{H\ell}{N}\,dt \\ &= V\oint H\,dB. \end{aligned} \tag{6}$$

Here, $V = A\ell$ is the volume of the iron core and $\oint H\,dB$ is the area enclosed by the hysteresis curve (in units of $H \times B$).

Estimate the area enclosed by the 0.1 A hysteresis curve and hence estimate the power dissipated in the transformer at 50 Hz.

$$\boxed{\text{Power = (Area of curve)} \times \text{(Volume of iron)} \times \text{(Frequency).}}$$

C2 ▷

Topic 2. Eddy Currents

The changing magnetic flux in the iron core of a transformer will induce an emf, not only in the primary and secondary turns, but also in the iron core. The iron core is a good conductor, so the currents induced in a solid iron core will be large. These currents are known as eddy currents and are undesirable, since they heat the core and result in power losses (in addition to the hysteresis losses). Furthermore, the eddy currents flow in a direction which, by Lenz's law, acts to weaken the flux created by the primary coil. Consequently, the current in the primary coil required to produce a given B field is increased, so the hysteresis curves are fatter along the H axis.

The magnitude of the eddy currents is proportional to the operating frequency, since the induced voltage in the iron is proportional to the rate of change of flux. At high frequencies, it becomes impractical to use iron cores in transformers and it is necessary to use either air cores or ferrite cores. Ferrites (as used in transistor radio antennas) are strongly magnetic and behave almost as insulators, so the induced eddy currents are very small.

Even at 50 Hz it is impractical to use solid iron cores in transformers or inductors. In practice, it is necessary to construct the core from thin strips of iron, known as *laminations*, which are coated with varnish to provide good electrical insulation. The eddy current paths are then broken (see Fig. A5-5), but smaller currents do flow within each lamination and limit the operating frequency to about 1 kHz. The transformer used in this experiment is made from a stack of 39 such laminations (they are easily visible).

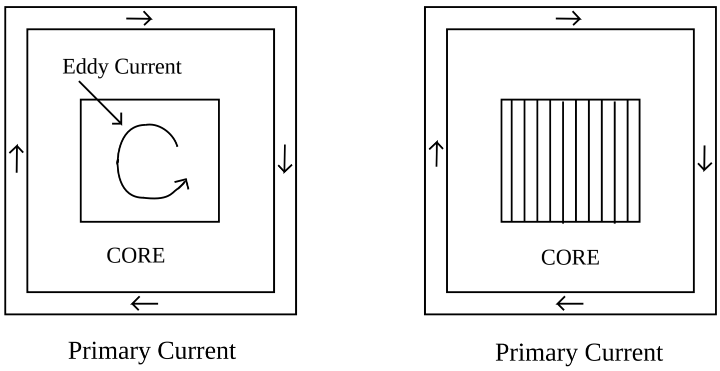

Fig. A5-5 Eddy current paths are broken by laminating an iron core

Procedure

1. To observe the effect of eddy currents, connect the circuit shown in Fig. A5-4, but use the $N = 30$ turn coil as the primary coil and the $N = 100$ turn coil as the secondary. This will allow you to saturate the core at frequencies up to about 500 Hz.

2. Because the impedance of the circuit changes with frequency, the current will vary as you change the frequency. You will need to adjust the power supply voltage as the frequency changes.

Remember to keep the current below $1.2\,\mathrm{A}$.

   Increase the oscillator frequency from 10 Hz to 500 Hz and note the ‘fattening’ of the hysteresis curve at the higher frequencies. Keep the primary current fixed at $1.0\,\mathrm{A}$ as you do this. The width of the hysteresis curve can be measured in terms of the coercive force H_c (see Fig. A5-3). Use the cursors on the oscilloscope display to do this.

   Plot a graph of H_c vs. frequency. Explain why the curves get fatter.

3. A ferrite transformer with N_1 primary turns and N_2 secondary turns has been placed in an oven with connection terminals outside the oven. The oven will be used in the

next topic to examine the effect of heating the ferrite. The ferrite core has dimensions of cross-sectional area A and length ℓ. The values of N_1, N_2, A and ℓ are marked on the experimental apparatus.

Using the same circuit as Fig. A5-4, examine the ferrite hysteresis curve for a primary current of amplitude 0.3 A and at frequencies over the range $50\,\mathrm{Hz} < f < 10\,\mathrm{kHz}$. In this case it is recommended that you set the sample rate on the oscilloscope to 250 kSa and apply the bandwidth limit filter to both channels. Note that the curve fattens slightly at high frequencies, but not nearly as much as the laminated iron core. Make a table of H_c values vs. frequency - a graph may not be necessary in this case. Record the coordinates (in T and $\mathrm{A\,m^{-1}}$) of the tip of the curve at $f = 1\,\mathrm{kHz}$. This coordinate may be useful when completing the next topic, as a point of comparison between the temperature response curve that you will plot and the room temperature situation.

C3 ▷

Topic 3. Curie Point for Ferrite

When magnetic materials are heated, thermal energy destroys the ability of magnetic domains to align along an external magnetic field. As the temperature rises, the magnetisation decreases until a temperature, called the Curie point, is reached at which M becomes very small.

Procedure

1. Reconnect the setup by replacing the transformer with the ferrite in the oven. The temperature is recorded by means of an electronic thermometer; the sensor is a thermocouple which is in good thermal contact with the ferrite which is in the oven. Record the current temperature (which should be near room temperature), then switch on the oven.

2. Adjust the frequency to $f = 1$ kHz and current to $i = 0.3$ A. As the oven heats up you will find that the current increases (why?). When the temperature has increased as far as you let it (see next two steps) you may wish to readjust the current back to 0.3 A.

3. Comment on what happens to the hysteresis loop as the temperature increases. In order to illustrate your observation, you may like to make rough sketches of the hysteresis curve at various temperatures as the temperature rises, or alternatively include representative screen dumps from the oscilloscope display in your log book.

4. When the temperature reads 100° C, switch off the oven. You will observe that even though the oven is switched off, the temperature will continue to rise to some value in excess of 130° C, and then begin to fall. When it does begin to fall, switch the oscilloscope back to Y-T mode and turn channel 2 (which measures B) to maximum sensitivity. Measure B in mV peak to peak (p-p) and H in V p-p. Make measurements of these quantities at various temperatures as the temperature falls, for example at 2°

intervals. Since the relative permeability changes rapidly near the Curie point, it is important to ensure that you record enough points in this region. You can stop making measurements once you are certain that you have let the temperature fall far enough to give you the data you need for a determination of the Curie point.

Plot a graph of relative permeability μ_r $(= B_0/\mu_0 H_0)$ as a function of temperature.

(The value of μ_r for this sample refers to a value of $H = N_1 i/\ell$. The dimensions of the ferrite transformer are given in the previous topic.)

You should find that μ_r decreases with increasing temperature towards the vacuum value $\mu_r = 1.0$. It never gets as low as 1.0, but we can extrapolate the steepest part of the μ_r vs. T curve towards $B = 0$ and define the intersection with the T axis as the Curie point. Use your results to estimate the Curie point for ferrite.

Conclusion

Comment on the significance of your observations in this experiment. For example, how much benefit does a ferrite core promise compared to an iron core? What is the significance of the Curie point to transformer operation?

C4 ▷