T5

Ferromagnetic Materials

You will measure current and voltage from a measurement circuit containing a ring of silicon-iron operating at 50 Hz over a wide range of peak magnetizing current. The complete ring is made up of thin annular laminations of silicon-iron (about 0.5 mm thick) as used in transformers and motors.

Schedule

Preparation time	:	3 hours
Lab time	:	3 hours

Items provided

Tools	:	n/a
Components	:	n/a
Equipment	:	Oscilloscope, AC power transformer, Integrator Magnetic ring with Si-Fe core, search coil, volt metre
Software	:	n/a

Items to bring

Essentials. A full list is available on the Laboratory website at https://secure.ecs.soton.ac.uk/notes/ellabs/databook/essentials/

Before you come to the lab, it is essential that you read through this document and complete ***all*** of the preparation work in section 2. If possible, prepare for the lab with your usual lab partner. Only preparation which is recorded in your laboratory logbook will contribute towards your mark for this exercise. There is no objection to several students working together on preparation, as long as all understand the results of that work. Before starting your preparation, read through all sections of these notes so that you are fully aware of what you will have to do in the lab.

> **Academic Integrity** – *If you undertake the preparation jointly with other students, it is important that you acknowledge this fact in your logbook. Similarly, you may want to use sources from the internet or books to help answer some of the questions. Again, record any sources in your logbook.*

Revision History

September 20, 2012	Barry Bailey (bmb) David Oakley (do)	Minor modifications and Optional Additional Work added
September 12, 2012	Prof. George Chen (gc)	Version 10

1 Aims, Learning Outcomes and Outline

This laboratory exercise aims to:

- Classify the magnetic materials
- Understand the behaviour of ferromagnetic material
- Construct and observe B-H loop (hysteresis)
- Understand the initial magnetisation curve
- Observed waveform of the magnetic field strength *H*

Having successfully completed the lab, you will be able to:

- Characterise magnetic materials
- Select magnetic materials for a particular application

Ferromagnetic materials are good conductors of magnetic flux and it is important to know the precise characteristics of different materials. Understanding these characteristics are important in industry and modern technology as they are used as the basis for electrical and electromechanical devices such as electric motors and transformers.

In this exercise you will determine these characteristics by the construction and observation of B-H loop (hysteresis) and observing the waveform of the magnetic field strength *H*.

---

2 Preparation

Read through the course handbook statement on safety and safe working practices, and your copy of the standard operating procedure. Make sure that you understand how to work safely. Read through this document so you are aware of what you will be expected to do in the lab.

2.1 Introduction

Answer the following questions:

- *Why the measurement circuit used is able to measure the magnetic behaviours? Can you propose an alternative system that is able to characterise magnetic materials?*
- *What are soft and hard magnetic materials? How they are defined?*
- *What are typical applications of hard and soft magnetic materials?*
- *How does the initial permeability of a ferromagnetic material change with magnetic strength?*
- *What is the role of silicon in Si-Fe ferromagnetic materials?*

2.2 Basic Principles

A ferromagnetic material is a good *conductor* of magnetic flux. The magnetic flux density B is simply related to the magnetic field strength H as $B = \mu_o H$ in air, where μ_o is called the permeability of free space ($4\pi \times 10^{-7}$ H m^{-1}), and in iron as

$$B = \mu_o H + M \tag{1}$$

where M is the magnetization vector. In fact both B and H are also vectors, i.e. have magnitude and direction, but in the simple ring sample used in this experiment the vectors have single components only and are parallel.

In a linear material $M = \mu_o \chi_m H$ where χ is a constant known as the *magnetic susceptibility*. Substituting in Equation (1):

$$B = \mu_o(1 + \chi_m)H = \mu_o \mu_r H \tag{2}$$

where μ_r is the relative permeability. In a ferromagnetic material μ_r will be of the order of at least 100, or considerably more, **but is not constant in practice**. We therefore need to return to Equation (1) and make measurements on each type of ferromagnetic material. A brief outline of the mechanisms involved follows.

Ferromagnetic materials are made up of domains which are already magnetized in the sense that each domain contains aligned magnetic dipoles formed by electron spin. When the sample of material is in an unmagnetized state the domains are so aligned that their net magnetization cancels. For example, in an iron crystal there are six directions of `easy' magnetization: the positive and negative directions along three orthogonal axes. If we assume, for the purpose of the argument only, that all domains are the same size, then in each of the ‘easy’ directions there will be as many domains pointing in the positive as in the negative direction. Now if a small magnetic field is gradually applied to the unmagnetized crystal nearly parallel to one of the easy directions, the domains with polarity in the same direction, i.e. assisting the applied field external to themselves, begin to grow at the expense of adjacent parallel domains with opposite polarity, by virtue of small movements of the domain walls. This process is virtually loss free if it takes place slowly.

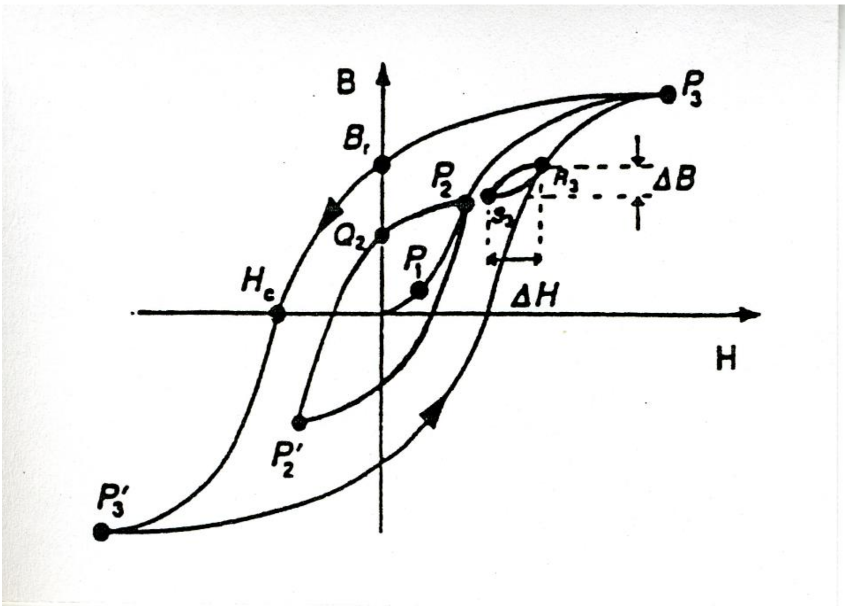

FIGURE 1: Hysteresis loops for a ferromagnetic material

Now consider a sample made up of a large number of crystals, each containing many domains, in the form of a ring on which there is a uniformly wound toroidal magnetizing winding producing a uniform applied field H parallel to the internal axis of the ring cross-section. This configuration gets over the problem of possible differences between the applied and the local field because there is no surface magnetic polarity present. Thus, with a simple search coil to measure the corresponding flux density B, a curve of B against H, starting with an unmagnetized ring, can be drawn as shown in Figure 1. The previously described process with a low value of H applied, takes us to point P_1. If this field is removed the operating point drops back to the origin because the process is reversible. To reach the higher point P_2, the domains already aligned with the field direction continue to grow, other opposing domains completely reverse, and those at other angles reverse polarity if this brings them more nearly into line with the applied field. All this activity involves extensive domain wall movement and the expenditure of energy. As a result when the field is reduced to zero, the flux density only drops to the point represented by Q_2, and if the applied field is then cycled between equal negative and positive maximum values, the complete loop $P_2P'_2$ is repeatedly traversed. This is known as a *hysteresis loop*, derived from a Greek word meaning 'to lag', and it can be shown that the expenditure of energy per cycle is given by the area of the loop. Alternatively, rising up the initial magnetization curve (also called the normal magnetization curve) to the higher point P_3 takes the material into magnetic saturation whereby almost complete alignment of the domains in the field direction has taken place.

Symmetrical hysteresis loops, known as major loops, can be formed from any points such as P_2 or P_3. The value of flux density at which $H = 0$ on any loop is known as the *remanent density* B_r and the value of H at which $B = 0$ is the *coercive force* H_c. The so-called *permanent magnetic materials* operate in the second quadrant of Figure 1 and require a very high coercive force, or coercivity, to prevent demagnetization during operation.

Hysteresis loops do not have to be symmetrical. An important example occurs if we are on a major loop such as that represented by P_3, P'_3 in Figure 1 but stop at point R_3 and begin to reduce H again but only by a small amount to point S_3. By causing H to oscillate by ΔH produces the minor hysteresis loop shown. The mean slope of this loop, i.e. $\Delta B/\Delta H$, is known as the *incremental permeability* μ_i.

2.2.1 Measurement of H and B

The magnetic field H produced by a uniformly wound magnetizing winding of N turns on the ring is given by

$$H = \frac{Ni}{2\pi R} \qquad (3)$$

where R is the mean radius of the annular ring. Equation (3) is only true if $t << R$ where t is the radial thickness of the ring as shown in Figure 2. Only a few turns of the magnetizing winding are illustrated.

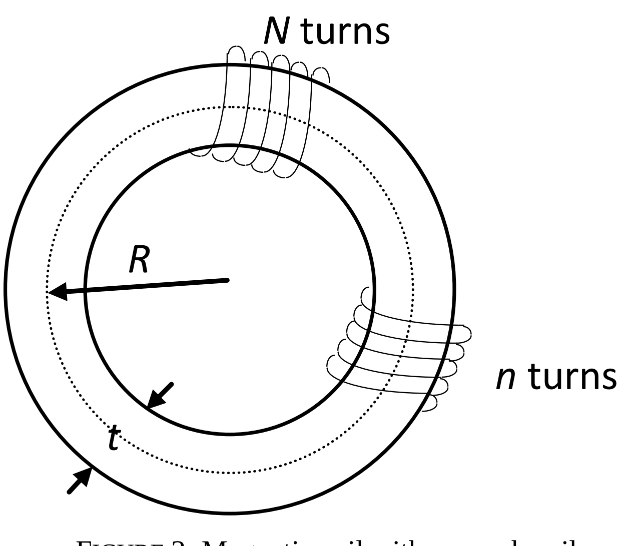

FIGURE 2: Magnetic coil with a search coil

The magnetic flux density B, on the other hand, can be measured by making use of Faraday's law,

$$emf = -\frac{d\Psi}{dt} = -n\frac{d\Phi}{dt} \tag{4}$$

where Ψ is the total magnetic flux linking a search coil of n turns wound on the sample in the same way as the magnetizing winding. Since the same flux Φ links every turn, $\Psi = n\Phi$. Now B is approximately uniform over the ring cross-section (since H is approximately uniform) so that $\Phi = B\,A$, where A is the cross-sectional area of the ring. Thus

$$emf = -nA\frac{dB}{dt} \tag{5}$$

B can therefore be found by integrating the emf with respect to time.

---

3 Laboratory Work

Connect up the magnetizing circuit involving the N turn magnetizing winding, as shown in Figure 3. A voltage directly proportional to the current is obtained across a 1Ω resistor and fed to the horizontal channel of the oscilloscope (set to 1 V per division). The output of the n turn search coil (Equation 5) is fed to the vertical input (set to 100 mV per division) via an integrator, the circuit of which is given in the Appendix. **Both channels should be dc coupled**.

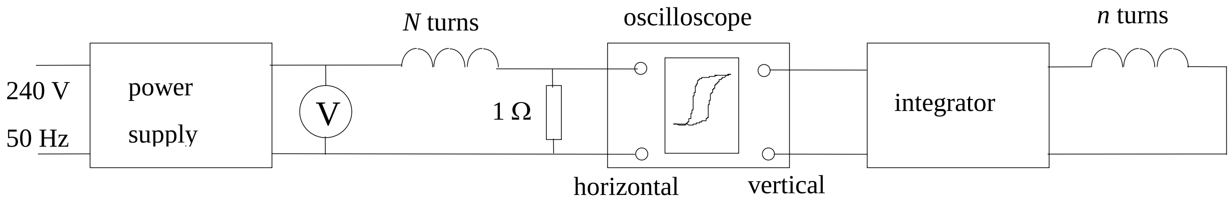

FIGURE 3: Electrical Circuit

Since the magnetizing winding is voltage driven from a sinusoidal supply, the flux in the ring, and hence the flux density, varies sinusoidally with time. Thus Equation (5) gives for the emf, e,

$$e = -nA\frac{d}{dt}(\hat{B}\sin\omega t) = -nA\omega\hat{B}\cos\omega t \tag{6}$$

where $\omega = 2\pi f$. With e as the input to the integrator, the output v_1 is given by

$$v_1 = -\frac{1}{CR}\int e\,dt = -\frac{nA}{CR}\hat{B}\sin\omega t \tag{7}$$

R = 12000 Ω and C = 1 μF. Also n = 5 and A = 510 mm^2. Thus the peak value of B is given by:

$$\hat{B} = \frac{CR\hat{v}_1}{nA} = 4.706\hat{v}_1 \quad \text{(T)} \tag{8}$$

where $\hat{v}_1$4 is a peak value and can be read from the oscilloscope. If a voltmeter is used it will indicate the rms value $(\hat{v} = \sqrt{2}\,v_{rms})$5.

From Equation (3) with N = 180 and $2\pi R$ = 0.566 m, H = 318.0 i (A m^{-1}). The current, and therefore H, will not be sinusoidal due to the nonlinearity of the magnetic circuit. The oscilloscope will monitor the voltage v_2 across the 1 Ω resistor and therefore

$$v_2 = i \qquad \text{and} \qquad H = 318\,v_2 \quad (\text{A m}^{-1}) \tag{9}$$

3.1 Stages of the Experiment

1. Increase the supply voltage to 30 V (rms) and check the peak values of v_1 and v_2 so that you will be able to decide on the magnitude of the axes for your *B/H* sketches on graph paper (v_1 vertical and v_2 horizontal, with the origin at the centre).
2. Demagnetize the sample by slowly reducing the supply voltage to zero. (This cycles the material through hysteresis loops of decreasing size and is a standard method of demagnetization).
3. Set the supply voltage to 1 V. With the oscilloscope in x-y mode, observe the hysteresis loop and sketch it as carefully as possible on your graph paper. Pay particular attention to the accurate location of the positive and negative tips of the loop.
4. Switch to normal mode (i.e. with time base) and sketch the *H* wave (v_2) as a function of time.
5. Repeat steps 2, 3 and 4 with supply voltages of 4, 12, 24 and 30 V in turn. Sketch all *B/H* loops on the same graph.

   Consider the effect on the output (sensor coil) waveform if you increased the supply voltage >30V.

6. Form the initial magnetization curve by joining the tips of the hysteresis loops, filling in one or two more points where necessary (but without drawing more loops).
7. Using Equations (8) and (9), mark off the vertical *B* scale in Tesla (T) in 0.5 T steps, and the horizontal *H* scale in Am^{-1}, in intervals of about 20 Am^{-1}.

   From these results what, if any conclusions can be drawn of the properties of the materials.

---

4 Optional Additional Work

Marks will only be awarded for this section if you have already completed all of Section 3 to an excellent standard and with excellent understanding.

There are two more samples of magnetic materials widely used electrical and electronic devices and equipment available for further investigation. Ferrite and mumetal have very different characteristics. Please note the number of turns of both the magnetising (N) and sensor (n) windings and choose appropriate ranges for B & H ranges on the oscilloscope.

Considering these results can you suggest a device or piece of equipment that they could be used for, and why?

Appendices - The Integrator

This consists of a buffer amplifier followed by the integrator circuit as shown below.

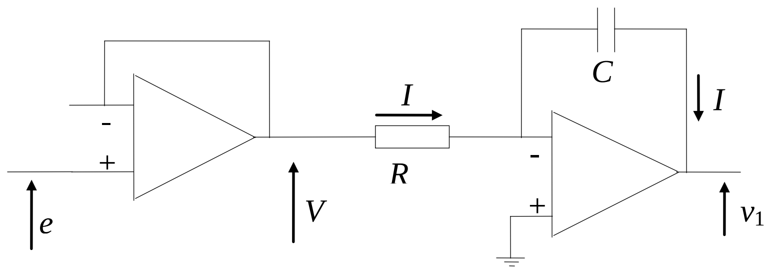

FIGURE 4: Buffer Amplifier and Integrator

The current through the capacitor $= I = -C\dfrac{dv_1}{dt}$

and equals to the current through the resistor $= \dfrac{V}{R}$

Hence $v_1 = -\dfrac{1}{C}\int I dt = -\dfrac{1}{C}\int \dfrac{V}{R} dt = -\dfrac{1}{RC}\int V dt = -\dfrac{1}{RC}\int e dt$