University of Tasmania

Second-year laboratory work

KYA212

The hysteresis of iron

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Safety

General information regarding lab safety can be found on POLUS, the lab website, whereas experiment-specific safety considerations are listed here.

Hazards

This experiment involves the creation of strong static magnetic fields. A serious hazard is posed to anyone with ferrous surgical implants and/or bioelectronic devices. Magnetically susceptible jewellery should be removed, and particular care should be taken with analogue watches and any form of magnetic storage media, as exposure to the fields may result in permanent damage.

A risk assessment for this activity has been undertaken and approved by the relevant university authority; it can be accessed here.

Summary

Hysteresis is the phenomenon where the state of a system depends on its history. In this experiment, the hysteresis of a ferromagnetic material is investigated, and the relation between the magnetic flux density **B**, magnetisation **M**, and the magnetic field **H** is explored and used to estimate the permeability of this material.

Experiment objectives and learning outcomes

The primary objective of this experiment is to construct a system capable of creating the appropriate conditions to measure a hysteresis loop, measure a hysteresis curve for iron, and extract a value for the magnetic permeability of iron.

Following this experiment, it is expected that you will:

- Understand the origins of hysteresis for a ferromagnetic system
- Be familiar with the construction of special-purpose circuits using operational amplifiers ("op-amps")

Introduction

Let us perform a thought experiment: we collect two identical socks from a bedroom from two locations: a drawer, and the floor. We now raise both socks one meter from the ground, release them, and carefully measure how long it takes for each to reach the ground. For the drawer sock, we measure 450 ms, but for the floor sock, we measure 650 ms. How can this be? These were identical socks, and save for their previous location, but we are measuring different states of the system when we would expect to measure the same state. What is going on?

The above example is obviously contrived and is unphysical, there exist real physical systems which display exactly this kind of behaviour, that is, the state of the system will depend on its history in a phenomenon known as *hysteresis*[1]. The most famous system which displays hysteresis is a ferromagnetic material in an external magnetic field, but hysteresis appears in mechanics (elastics, adsorption), engineering (backlash, control systems, aerodynamics), biology (neuroscience, immunology), and other areas. Whilst one can get lost in detailed modelling of hysteresis, with a rudimentary model of the process it is possible to not only observe the hysteresis of iron, but also to extract the permeability of the ferromagnetic material.

Background

Pre-lab exercises

Pre-lab questions can be found sprinkled through the introductory section. These are to be completed and submitted *before* you commence a new experiment. The information needed to complete the exercises is contained in the experiment background section, your course notes, or in the appendices; however, your own independent research is highly encouraged. Make sure to include references where material has been foraged from elsewhere; this is not only "good form", but making notes of this kind - where to find useful information - is essential should you need to return to the origin of some information.

[1]The term hysteresis is derived from the ancient Greek word meaning *to lag behind*

Context

Natural systems which display hysteresis are not uncommon: for example, there exist materials in which phase changes temperatures for melting and freezing are not the same! This means that there will be a range of temperatures over which the material will be either solid or liquid, depending on its previous state[2]. The specific area of interest in hysteresis for this experiment is the case of ferromagnetic material in an external magnetic field. This is a seemingly simple operation which has applications from the humble fridge magnet through to magnetic storage and advanced manufacturing.

Even though magnets have been ever present, it wasn't until the late 19$^{\text{th}}$, and early 20$^{\text{th}}$ centuries that people started to study the details of (de)magnetisation and hysteresis. Necessarily, systems which display hysteresis are non-linear, and thus can be hard to model; however, observation and characterisation of hysteresis is relatively straightforward. This, coupled with some determination one can make some headway through the modelling morass.

Magnets, how do they work?[3]

To understand hysteresis requires a firm foundation of the origins of magnetism, and how the magnetism of a material is manipulated.

Prelab 1 *Big Heavy Magnets (BHM)*

What are $\mathbf{B}$, $\mathbf{M}$, and $\mathbf{H}$ physically? How are they related?

Magnetism is often treated as a bogeyman: theoretically it is hard to explain, mathematically it is usually one's first encounter with the cross product, and experimentally it is hard to measure accurately, all of which combine to cast a long shadow. It is indeed true that the details are magnetism are complex and a foundation of intermediate physics is required to start to discuss the topic, but fortunately, we are in a second-year physics course.

Magnetism has its origin on the quantum scale, ultimately arising from the *spin* of the system under consideration. Spin is a fundamental quantity in quantum mechanics (which you will start to explore more rigorously in your third-year physics units), and without getting into the weeds, it refers to the *intrinsic* angular momentum of a particle (as compared to say, orbital angular momentum). Any angular momentum can give rise to a magnetic dipole, and it is these dipole moments in which we are interested. For simplicity, our discussion is going to be limited to solids in which the material properties are largely determined by the "free" electrons in the material (e.g. metals)[4].

Regions within materials where the magnetic moments of electrons are aligned in the same direction are called *magnetic domains*. A typical chunk of iron contains many magnetic domains. If these domains are randomly oriented, then the total magnetisation from one region will tend to be cancelled out by its neighbours, and $\mathbf{M} \approx \mathbf{0}$. On the other hand, if all the domains are aligned with one another, then the magnetisation will be a maximum, $\mathbf{M} = \mathbf{M}_{\text{max}}$, and the object is said to be *magnetically saturated*.

Prelab 2 *Types of magnetism*

What is ferromagnetism, what is its origin, and how does it differ from paramagnetism and diamagnetism?

In a material, these electron spins can respond to an applied magnetic field $\mathbf{B}$, which gives rise to bulk magnetic properties of the material.

[2]so-called antifreeze proteins are an excellent example, and which keep fish in cold places alive!
[3]for the uninitiated
[4]Once again, see third-year physics

Under the influence of an external magnetic field, randomly oriented domains can become aligned which gives rise to bulk magnetic properties of the material. A schematic of this is shown in Fig. 1.

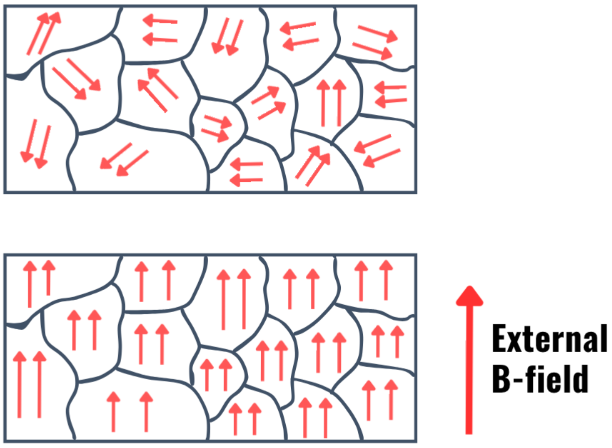


Figure 1: A sample of iron can contain many regions (domains) where the spins are aligned randomly (upper panel). When a magnetic field is applied, the spins can align in the direction of the magnetic field (lower panel).

To make things easier to quantify, we can reduce the problem by considering only the components of fields in the direction of the external field. Shown in figure 2 is a plot of the magnetisation as a function of the applied field starting when starting with a magnetisation of 0, that is, an un-magnetised sample. As the external field increases, so too does the magnetisation, until magnetic saturation is approached and the slope of the curve levels off. Once $\mathbf{M}_{\text{max}}$ is reached, any further increase in H produces no additional magnetisation.

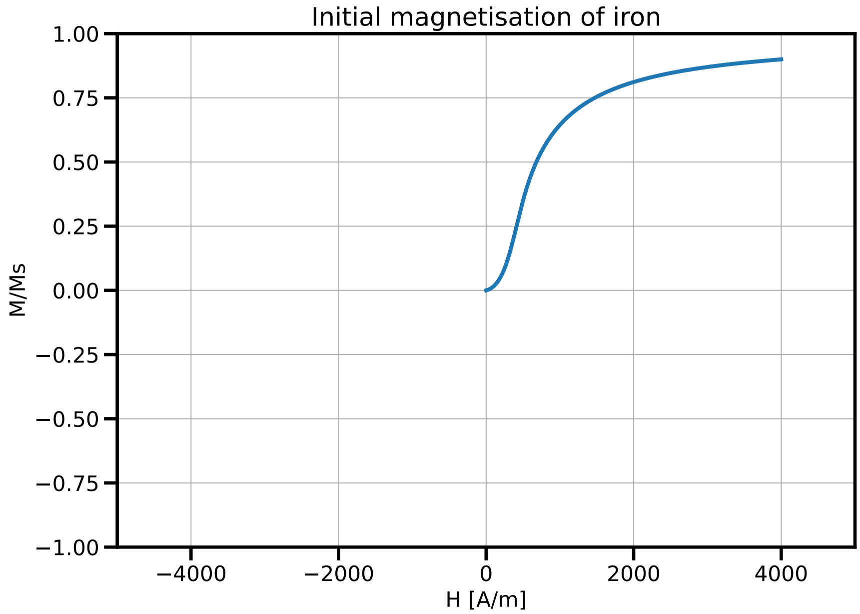


Figure 2: A plot of the magnetisation as a function of the external magnetic field strength

Demagnetisation

Demagnetisation (as you might guess...) is the opposite process to magnetisation; however, it is delightfully more complicated process thanks to hysteresis. Thinking about a magnetised ferromagnet, this can be demagnetised by removing the alignment between magnetic domains, but critically, these domains don't immediately reorient in the presence of an external field. Rather, they stay in their original orientation until the so-called magnetic *pinning* is broken, and then more domains will reorient at the magnetisation will change. The details of exactly what happens during the destruction the alignment between neighbouring domains is fairly complex, but a qualitative picture is largely sufficient to understand why hysteresis appears. A typical hysteresis curve, that is, a plot of external magnetic field versus magnetisation is shown in figure 3.

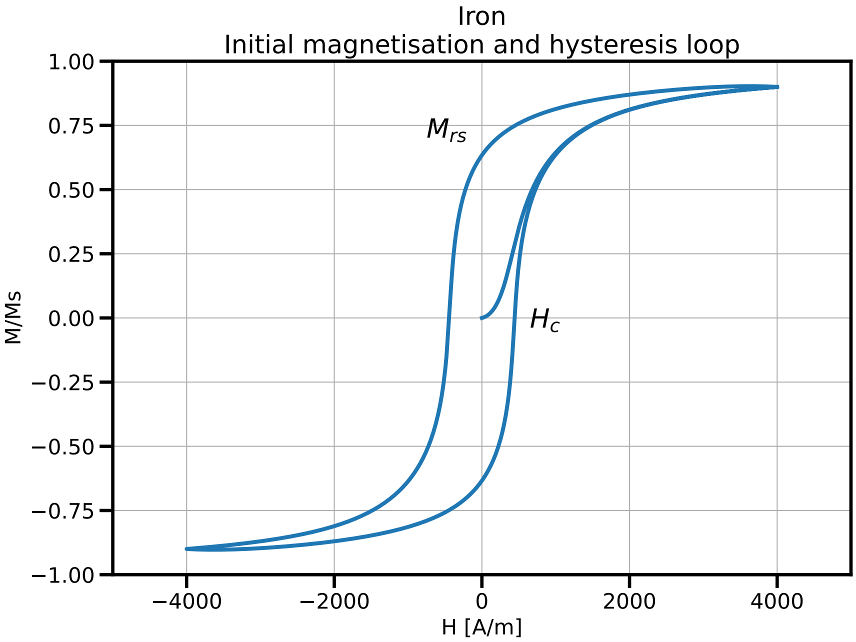


Figure 3: A plot of the magnetisation as a function of the external magnetic field strength

Prelab 3 *Symbolic to meaningful*

The points H_c and M_{rs} shown on figure 3 represent the *coercivity* and *saturation remanence*. What to these values represent physically?

Demagnetisation may also refer to completely removing the magnetisation from the sample, not only changing the magnetisation once it is saturated. One way remove the magnetisation completely is to apply a alternating magnetic field to the sample whilst slowly decreasing the amplitude of this field, in a process known as *deguassing*.

Prelab 4

Speculate on why applying an alternating magnetic field can reduce the residual magnetisation of a sample. Additionally, propose another method for demagnetising the sample.

Modern research into the magnetisation of materials employs three-dimensional magnetic microscopy. It is now possible to map magnetic domains in samples, measure individual spins in materials, in addition to preparing and evolving novel magnetic state. Understanding the distribution of magnetic domains and their evolution in the presence of an external field is critical in material science, and a recent publication [1] demonstrates how X-ray magnetic tomography[5] was used to observe the three-dimensional magnetic domain structure changes

[5] Essentially, magnetically sensitive CT scan

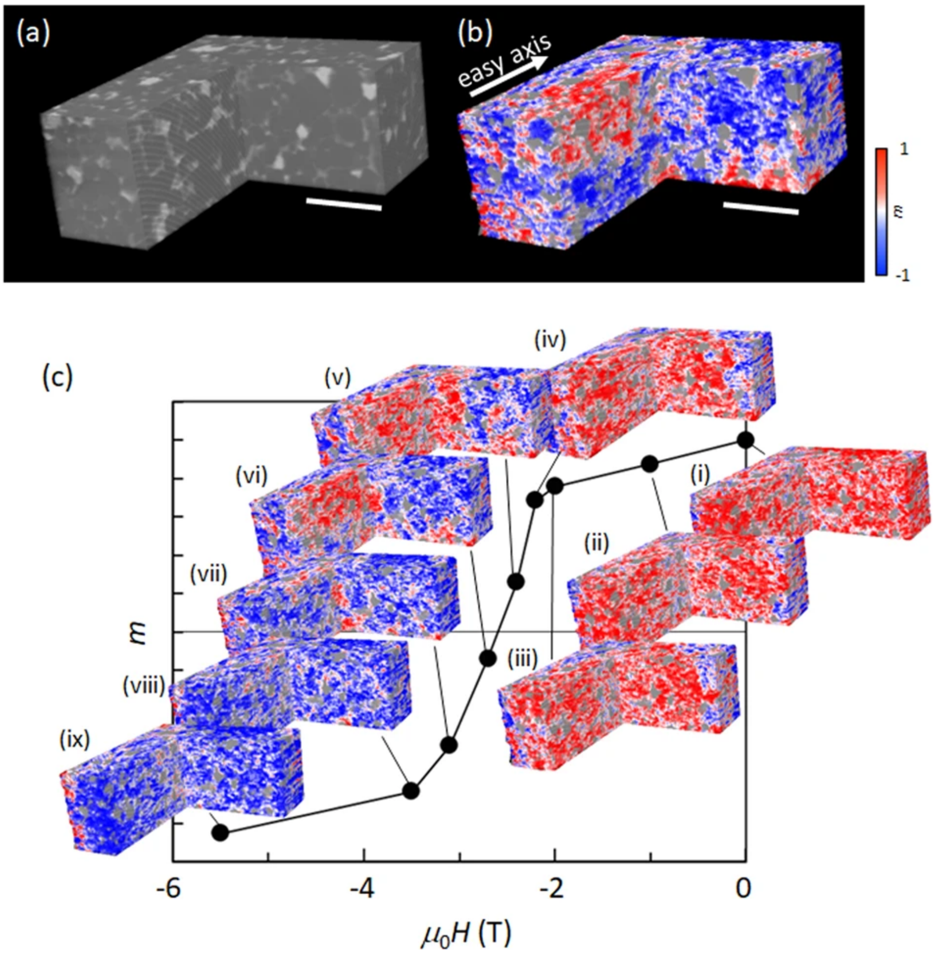


Figure 4: Cutaway images from [1] showing how the magnetic domain alignment of a neodymium magnet changes throughout a portion of the hysteresis curve. The hysteresis curve proceeds from the snapshot at (i) to the snapshot at (ix).

of a neodymium magnet (Nd-Fe-B) as it goes through a hysteresis curve. Their results are shown in 4 where we can see how the alignment of the magnetic fields changes as we approach the two ends of saturation on the curve; pretty amazing!

Prelab 5

In physical terms, what is permeability? What is relative permeability? How do these relate? Derive an expression relating the permeability of the material, μ, to the measured quantities $\mathbf{B}$ and $\mathbf{H}$. From this, state how you can measure μ from your magnetisation curve?

An aside: modelling hysteresis

Modelling magnetisation is a hard problem. On the micro scale, that is, the scale of individual spins, the problem explodes with complexity depending on how far (i.e. how many "spins away") one considers the magnetic interactions significant. One the macro scale, the complex coupled dynamics of magnetic domains renders analytical models of bulk magnetic systems challenging. Perhaps the best evidence of this is the "Jiles–Atherton model", the most common model for hysteresis, was developed in 1984!

The mathematical details of the model are not particularly relevant for the experiment itself, but the model is to be explored computationally, and thus it is important to understand what exactly is being computed. It is also important to know what it is we want to compute! At the end of the day, a hysteresis curve shows a plot of the external field H versus the magnetic flux density B, so provided we can compute B we will be happy. As it turns out, we actually compute the magnetisation M, but since the flux density B in the material is given by

$$B(H) = \mu_0 M(H) \tag{1}$$

we are content. The model incorporates the effective field H_e inside the material, which is given by

$$H_e = H + \alpha M \tag{2}$$

where α is a dimensionless "mean-field" parameter which quantifies the coupling between domains in the material. It is then possible to calculate the *anhysteretic* magnetisation[6] through the relation [2]

$$M_{an} = M_s \left(\coth\left(\frac{H_e}{a}\right) - \frac{a}{H_e} \right) \tag{3}$$

where M_s [A/m] is the saturation magnetisation of the material and a [A/m] quantifies the domain wall density, and thus the magnetisation (roughly). We therefore have a method to calculate the magnetisation (and thus flux density), albeit via solving a nasty transcendental equation.

Whilst this might seem a bit much, keep in mind that our aim here is to gain an intuition for exactly is a hysteresis loop, and what physical parameters affect its shape. We are going to do this by explicitly computing the magnetisation as predicted from equation 3. But do not fret: the computational heavy lifting has been done for you, so you need only explore the parameter space and observe the results. We will be using a prepared `Jupyter` *notebook* to have a play, so in the event you need a crash course or refresher on how to drive `Jupyter` or execute `python` code, see the lab website.

Exercise 1 *Changing the domain wall density*

Visit the Jupyter notebook entitled *Hysteresis*[a], and use it to produce a set of plots showing the effect of changing a, the domain wall density. In an experiment, what control would one have over the parameter a?

[a] Alternatively, this can be accessed at https://github.com/Andy-UTAS/partII

The above calculation was only for the anhysteretic magnetisation; including the hysteretic component, the magnetisation as a function of the magnetising field is given by

$$\frac{\mathrm{d}M}{\mathrm{d}H} = \frac{1}{1+c}\frac{M_{an} - M}{\delta k - \alpha(M_{an} - M)} + \frac{c}{1+c}\frac{\mathrm{d}M_{an}}{\mathrm{d}H} \tag{4}$$

where k [A/m] quantifies the average energy required to destroy a pinning site (and thus the degree of hysteresis), c is the reversibility of magnetisation, and $\delta = \pm 1$ depending on the magnetising field H ($\delta = +1$ for an increasing field and $\delta = -1$ for an decreasing field).

Exercise 2 *Pinning site strength*

Return to the *Hysteresis* Jupyter notebook [a], and use it to produce complete hysteresis plots which demonstrate the effect of varying k. In your experiment, what determines the value of k?

[6] technically, this is only the isotropic component of the anhysteretic magnetisation

[a]Alternatively, this can be accessed at https://github.com/Andy-UTAS/partII

Exercise 3

Describe qualitatively (or sketch/plot) what the hysteresis loops would look like for nickel ($\mu = 100$) and for a high-permeability nickel-iron alloy such as "mu-metal" ($\mu \approx 10^5$).

Apparatus

The discussion of magnetisation in concert with the computational modelling of hysteresis should have crystallised what it is that we are trying to produce: a hysteresis curve. To do this, you have the following components, with a visual description of each component shown in figure 5:

1. A section of **cast iron pipe** which has been encased in a tightly-wound coil of wire. Together, this creates a toroidal electromagnet with an iron core. The coil has a mean radius of r_m and the primary coil has approximately $n_p = 480$ turns. The toroid has a *secondary coil* comprised of n_s turns, which allows one to probe the internal field of the iron core. A *pickup* coil will only have current when there is a change in magnetic field, but fortunately we are trying to produce a hysteresis curve, and thus will continually be changing the applied field. A schematic of this is shown in figure 6.
2. An **integrating amplifier** which will be used to amplify the signal. This integrating amplifier requires some careful attention to both understand and operate, with details on both of these provided in the reference section of POLUS.
3. A **rheostat**, which is a variable resistor.
4. A large **capacitor**.

   NOTE: The capacitor is a *polarised* capacitor, meaning that is will only function correctly when the voltage on the anode is greater than the cathode, and a failure to meet this condition can destroy the capacitor. Confirm with a demonstrator that the capacitor is correctly wired *prior* to powering on the circuit.
5. A **double-pole double-throw switch** which allows you to change the direction of current flow.
6. A ***picoscope 2000*** is provided for data logging and for which operational details can be found on POLUS.
7. A variable DC power supply.
8. Power supply to power the integrating amplifier.
9. 12V, 50 Hz, AC power supply.

Experiment

With the apparatus described and the relevant physics discussed, it is now time to design and execute the experiment that achieves the Experiment Objectives. Ensure that you describe the role/function of the (non-trivial) apparatus components that you use in your experiment.

Before you are able to take the data necessary to calculate the magnetic permeability for the iron toroid, you will need to construct two circuits.

Figure 5: Various components available for use in the lab. Descriptions of these are given below.

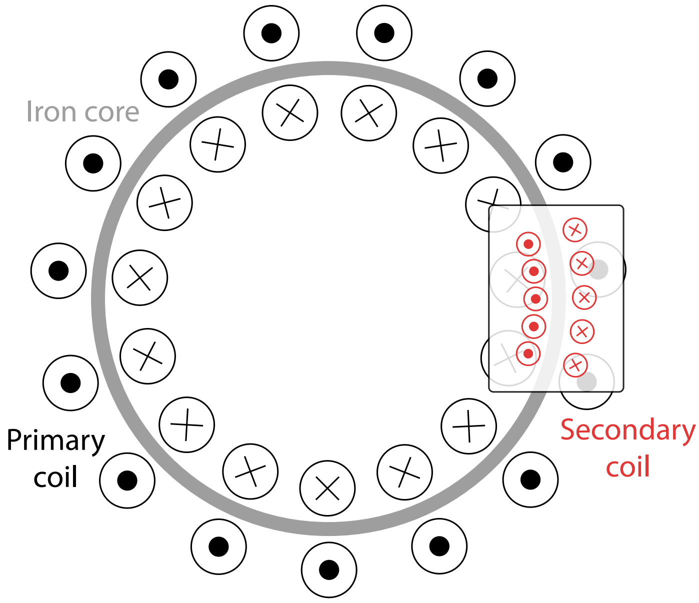


Figure 6: A simplified schematic of the apparatus

The first circuit - the **magnetisation circuit** - will allow you to take take the iron sample through the hysteresis loop. The hysteresis loop is the main observational result of this lab. It will contain elements to vary the voltage and also amplify the signal coming out of the iron toroid so that it can be more easily analysed.

The second circuit - the **demagnetisation circuit** - will (essentially) demagnetise the iron toroid, allowing you to measure multiple hysteresis loops, starting with an demagnetised sample. It is *extremely* likely - read: certain - that you will want to capture multiple loops as you refine your experimental method and data capture process to get the best hysteresis loop you can.

Read the notes carefully before you start to design and connect your circuit.

The magnetisation circuit

Let's think about the circuit we are going to make to measure the hysteresis curve. You will need to design and construct a circuit to take the iron sample around a hysteresis loop, producing a figure that is similar to Fig. 3. If we consider the hysteresis curve in Fig. 7 which has some key features highlighted, we need the circuit to go from point A to E and then back to B.

1. From point A to B we want to increase the circuit current from 0 to some maximum value.
2. From B to C we are decreasing the current back to 0.
3. At point C, we need a way to reverse the current.
4. To get from C to D we will increase the current to the same maximum value again having switched it to the opposite direction.
5. From D to E we reduce the current back to 0.
6. Then at E, we reverse the current again and increase it to get back to point B.

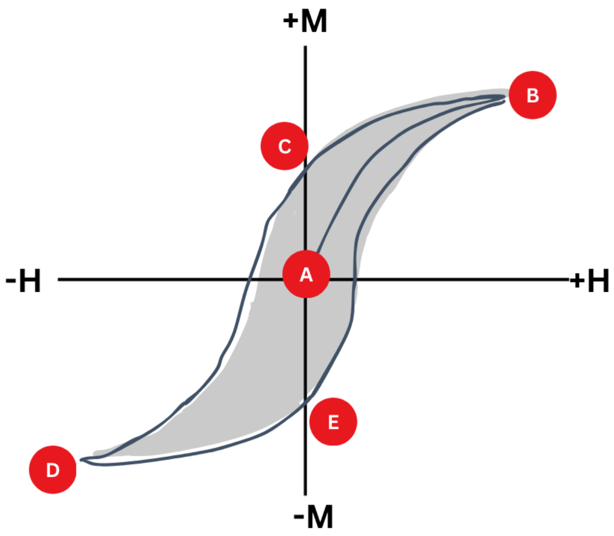


Figure 7: A broken-down hysteresis curve showing several points of interest.

A DC power supply is used for this circuit, and you can take advantage of the potential divider theorem to devise a control for the amount of current flowing through the primary coil around the toroid. That is, you must be able to start with the current at exactly zero, increase it steadily to some chosen maximum value, $I_{max} \approx 2$–3 A , and then reduce it steadily to zero again. You must then be able to reverse the polarity of the current, and repeat the process, increasing its magnitude to the same I_{max} as before and finally returning to zero.

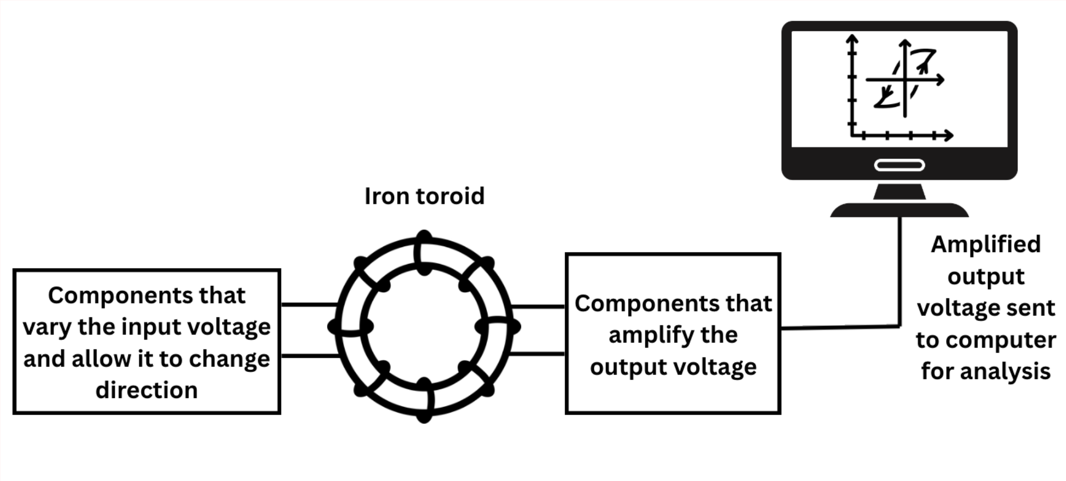
There are numerous potentiometers and switches available for use in constructing this circuit. Make use of the potential divider theorem in your work, and use a meter to confirm the resistance across the primary coil (it should be in the ballpark of 3Ω). It will be extremely convenient to use a *double-pole, double-throw* switch as a crossover, reversing the direction of current flow downstream of the switch with respect to the power supply. Ensure that no current greater than 4 A will flow in any loop (otherwise components may generate problematic amounts of heat), and design in a way of controlling the value of I_{max} so that smaller hysteresis loops can be obtained. It may be extremely helpful to start by drawing out the circuit diagram in advance before you connect any wires. Consult early and often with your demonstrator.

NOTE: Record the voltage on `channel A` of the data-logger. If the voltage output from the high-current circuit connected across the primary coil exceeds maximum voltage accepted by the data logger, it will saturate; think about how to prevent this. Test your circuit with the output connected across a multimeter or oscilloscope before connecting it up to the computer.

Exercise 4 *Creating an adjustable, high-current circuit*

With the points listed above, design a circuit that will allow you to take the ferromagnetic sample through a hysteresis curve. It should resemble the below sketch but with more details about which electrical components go where.

Note that you won't need all of the available components to do this.



1. When the adjustable high-current circuit is connected up across the primary coil, its output will be proportional to **H**. Feed this output to the X input of the data logger on the computer.
2. Include a schematic circuit diagram of your high-current circuit in your written report.

Exercise 5 *Data recording*

Now you are ready to take a few practice trips around a hysteresis loop. Don't try to record data yet; it's best to make sure things are working first. Connect a multimeter set to measure a DC voltage to the output of the amplifier and see what happens as you increase the current from 0 to some I_{max}, reduce it to 0, and then flip the polarity, taking the circuit from 0 to $-I_{max}$ and back. You could also connect X and Y voltages to an oscilloscope with its time-base switched off. You should see the spot trace out a hysteresis loop on the screen.

Now have a look at the data logger. We are using *PicoLogger* with channels A and B. The software is located on the desktop of the PC. Activate the channels and set the maximum voltage and sampling rate suitable for the experiment. What should the max voltage and sampling rate be? You should be able to see the live voltages for each channel. You can also choose a graph view. You may wish to do a practice run and familiarise yourself with recording, saving and downloading the data.

The demagnetisation circuit

After the iron toroid is taken through a hysteresis loop, there will be a residual magnetisation in the sample. In order to get useful results that aren't skewed by residual magnetisation, we need a way to effectively demagnetise the sample. This process is called *degaussing*, and we shall now build a circuit to accomplish this goal.

The circuit takes advantage of the potential divider theorem to vary the current through the primary coil using an AC power supply. The 12 V AC power supply provided will degauss the iron toroid very effectively if connected across the primary using a 7.5 Ω potentiometer. Start with the slider in the middle of the range, and gradually decrease the current through the primary coil over a period of several seconds. Calculate approximately what positioning of the potentiometer will limit the current through the primary to about 3 A. As you sweep the slider on the potentiometer, reducing the current amplitude, the AC current takes the primary through 50 hysteresis loops each second, each one smaller than the last. When the current reaches zero, the sample should be fully demagnetised.

Exercise 6 *The degaussing circuit*

With the information above, create a circuit that will degauss the primary toroid.
Consider:

- How will you know if it has worked, i.e. if the residual magnetisation has been removed from the primary coil?
- Are there any sources of error here?

Include a schematic circuit diagram of the degaussing circuit in your logbook.
Remember to discuss anything you're uncertain of with your demonstrators.

Exercise 7 *The pursuit of perfection*

You should now be able to demagnetise the iron, and take the iron around a full magnetisation (hysteresis) loop. Your goal is to produce a hysteresis loop, beginning from a demagnetised sample, with sufficient quality to allow for further analysis.

Analysis

You have collected data! This means that you have a bunch of numbers, and these numbers represent the voltages as seen by the *picoscope*, measured from the primary coil (V_A) and the voltages you have generated in the secondary coil (V_B). We now need to turn these voltages into something meaningful, namely **H** and **B** respectively.

The magnetic field

A current was used to generate a magnetic field. We need to relate these two quantities, so we can link V_A to H.

Exercise 8 *Calculating H*

Given a current I passing through the coil, what is the magnetic field strength H from the electromagnet?

HINT: Ampère's law might be of some use.

The magnetic flux density

The induced voltage from the secondary coil was fed into an integrating amplifier and measured. We need to unscramble the egg so we can relate V_B to B.

Exercise 9 *Induction*

How is the induced voltage $\mathcal{E}$ in the secondary coil related to $\mathbf{B}$?

HINT: Faraday's law might be of some use.

Exercise 10 *Integration*

Relate the magnetic flux density B to the voltage measured from the integrating amplifier V_B.

Exercise 11

1. Using the above results, convert your voltages into values for **B** and **H** and plot the curve of B versus H (hysteresis loops). Does the same reach saturation? What is the physical significance of the y-intercept of your graphs, and discuss any differences in the value of this intercept for the high and low current cases.

2. Use your magnetisation curve beginning at $\mathbf{M} = 0$ to plot the curve of relative permeability versus H. The permeability of a ferromagnetic substance is usually described by μ_{max}, the greatest value of μ between $H = 0$ and saturation. Find the value of μ_{max} as indicated by your data, and estimate errors as best you can. Is your result consistent with references found in textbooks, online, or in any assumptions you made in constructing your circuit(s)?

3. It takes energy to align magnetic domains. Where does the energy come from in this setup? Calculate the amount of power dissipated in the sample of iron when an alternating current with amplitude $I_0 = 1$ A and f = 50 Hz passes through it. What are some implications of this result?

References

[1] Makoto Takeuchi, Motohiro Suzuki, Shintaro Kobayashi, Yoshinori Kotani, Tetsuya Nakamura, Nobuaki Kikuchi, Anton Bolyachkin, Hossein Sepehri-Amin, Tadakatsu Ohkubo, Kazuhiro Hono, et al. Real picture of magnetic domain dynamics along the magnetic hysteresis curve inside an advanced permanent magnet. *NPG Asia Materials*, 14(1):70, 2022.

[2] Dieter Lederer, Hajime Igarashi, Arnulf Kost, and Toshihisa Honma. On the parameter identification and application of the jiles-atherton hysteresis model for numerical modelling of measured characteristics. *IEEE Transactions on magnetics*, 35(3):1211–1214, 2002.

Appendix