UM-SJTU JOINT INSTITUTE
PHYSICS LABTORATORY
(VP241)

LABTORATORY REPORT

EXERCISE 1
BASIC CHARACTERISTICS OF MAGNETIC MATERIALS

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1 Objectives

The goal of this exercise is to study the shape of the magnetic hysteresis loop and the magnetization curve, and understand how to use these characteristics to discuss properties of ferromagnetic materials. In this exercise these properties will be studied quantitatively using the concepts of the coercive field strength, the residual magnetic field and the magnetic susceptibility. The magnetization curve and the magnetic hysteresis loop will be visualized on the oscilloscope. Also, time permitting, the Curie temperature of a ferromagnetic material will be found experimentally.

2 Introduction and Theoretical Background

Magnetic materials are widely used in electric power industry, electronic devices, such as computers, and in information storage technology. Their basic properties can be discussed by studying the magnetic hysteresis loop and measuring the Curie temperature. The former provides information about how easy is to change properties of the magnetic material, and the latter characterizes the phase transition between from/to the magneti cally ordered phase.

2.1 Magnetization

Magnetic medium is defined as matter that can be magnetized, that is magnetic dipole moments in the material can be arranged into some ordered pattern. The process of magnetization can be described in terms of three quantities: the magnetic field **B**, the magnetization **M**, and the auxiliary magnetic field **H**. In the simplest case, these three quantities can be represented by their magnitudes and are related as follows

$$B = \mu_0(H + M) = (\chi_m + 1)\mu_0 H = \mu_r \mu_0 H = \mu H$$

where $\mu_0 = 4\pi \cdot 10^{-7}$H/m is the magnetic permeability of vacuum, χ_m is the magnetic susceptibility of the material, the dimensionless quantity $\mu_r = \chi_m + 1 = \frac{B}{\mu_0}$ is called the relative magnetic permeability of the material, and $\mu = \mu_r \mu_0$ is the material's(absolute) magnetic permeability. For a paramagnetic material, $chi_m > 0$ and μ_r is slightly greater than 1. On the other hand, for a diamagnetic material, $\chi_m < 0$ with the absolute value between 10^{-4} and 10^{-5} and μ_r is slightly less than 1. For a ferromagnetic material,$\chi_m \gg 1$, so that $\mu_r \gg 1$.

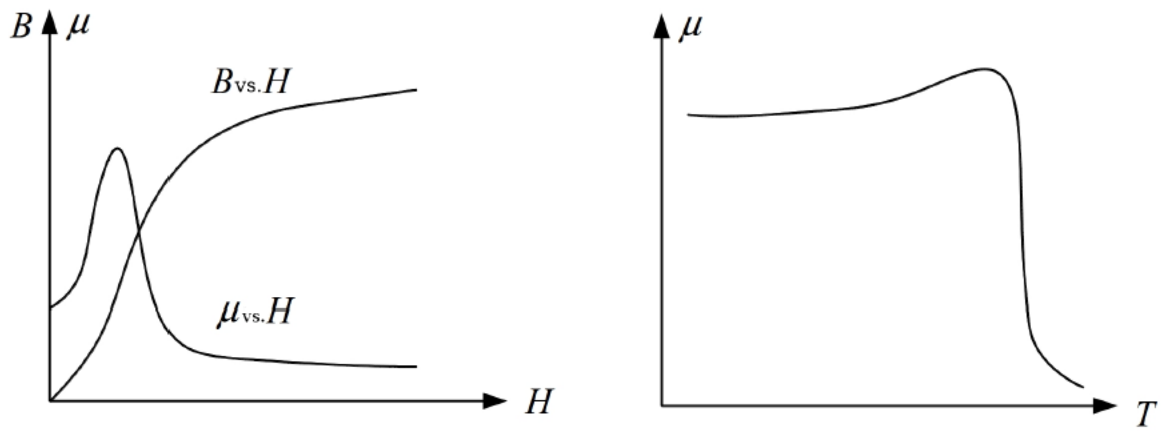

Figure 1: (left) The magnetization curve $B(H)$ for a ferromagnetic material and the curve $\mu(H)$. (right) A generic graph of the $\mu(T)$ curve for a ferromagnetic material.

The magnitudes of the magnetic field and the auxiliary magnetic field are related linearly in non-ferromagnetic isotropic materials, that is in such materials $B = \mu H$. However, for ferromagnetic materials the relationship is non-linear. In ferromagnetic materials there is a spontaneous magnetization (magnetic dipole moments are spontaneously oriented parallel to each other) that increases with the decreasing temperature. Figure 1 (left) shows a typical magnetization curve $B = B(H)$ with some features common to all ferromagnetic materials. Namely, when H increases, B increases slowly at the beginning and μ is small; then B and μ both rapidly increase as H increases; finally, B reaches a saturation level and μ rapidly decreases after reaching a maximum value. Figure 1 indicates that the magnetic permeability μ is a function of both the auxiliary magnetic field H (Figure 1, left) and the temperature T (Figure 1, right).

If the temperature is increased above a certain value, a ferromagnet will turn into a paramagnet, that is a material with randomly oriented magnetic dipole moments. This critical value of the temperature is called the *Curie temperature*, and on the graph μ vs. T it is the temperature corresponding to the point where the slope of the tangent line is maximum.

2.2 Magnetic Hysteresis

In addition to high magnetic permeability, ferromagnets have another important property, which is the magnetic hysteresis. When a ferromagnet is being magnetized, the magnetic field B depends not only on the current value of the auxiliary magnetic field H, but also on the previous state of the material, as shown in Figure 2. The curve OA, where the magnetic field B grows as the auxiliary magnetic field H increases, describes the process of magnetizing of an (initially demagnetized) ferromagnet. This curve is called the *magnetization curve.*

When the auxiliary magnetic field is increased to a certain value H_S, the magnetic field B hardly increases and reaches a saturation state. If then the auxiliary magnetic field is being decreased, the magnetic field B is not decreasing along the original path, but rather choosing another path $AC'A'$. Furthermore, when H increases from the value $-HS$, B will reach A along the curve $A'CA$, and finally form a closed curve. When $H = 0$, we have $|B| = B_r$, where B_r is called the *remnant magnetic field* (yielding the corresponding remnant magnetization). In order to make $B = 0$, an auxiliary magnetic field has to be applied in the reverse direction. When the auxiliary magnetic field reaches the value $H = -H_C$, where H_C is called the coercive field strength, the material is demagnetized and the magnetic field B, and hence the magnetization, is zero. Different ferromagnetic materials have different magnetic hysteresis loops with different values of the coercive auxiliary field strengths. Ferromagnetic materials with a large value of the coercive auxiliary

field are called *hard* magnetic materials, whereas those with a small one classified as *soft* magnetic materials.

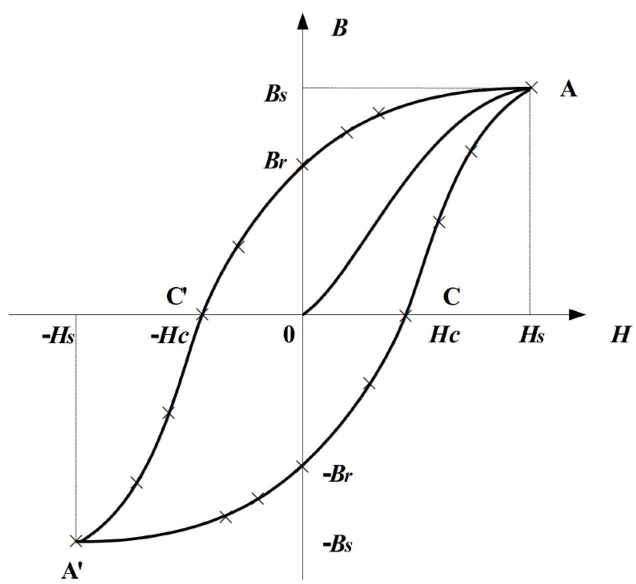

Figure 2: The magnetization curve and the magnetic hysteresis loop of a ferromagnetic material. The crosses indicate the points to be recorded to describe the loop.

2.3 Visualization on the Oscilloscope

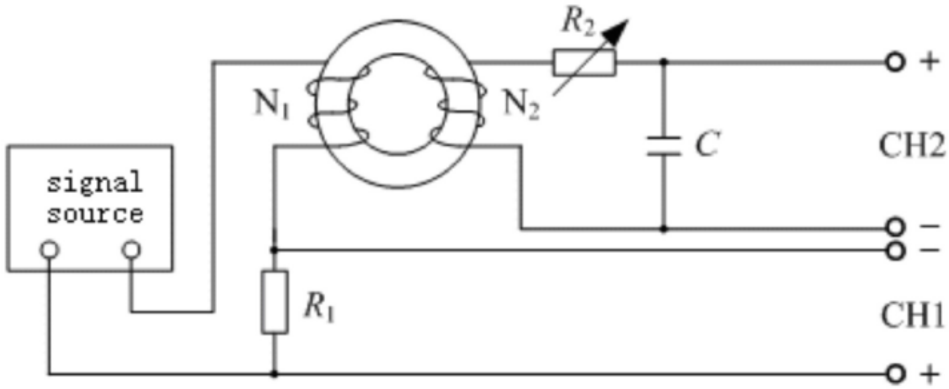

Figure 3: The electric circuit for visualization of the magnetization curve and the magnetic hysteresis loop on the oscilloscope.$R_1 = 10\Omega$ and R_2 is a variable resistor with maximum resistance of 2.2 kΩ.

Figure 3 presents a diagram of a circuit that is used to visualize the magnetization curve and the magnetic hysteresis loop on the oscilloscope. In this exercise they are studied for a ferromagnet sample that has an average magnetic path of L and the number of the turns in the coil is N_1. If the electric current through the coil is i_1, then according to Ampère's law

$$HL = N_1 i_1$$

In this case the input voltage for the deflection plate of the x axis channel of the oscilloscope is

$$U_{R_1} = R_1 i_1 = \frac{R_1 L}{N_1} H$$

where R_1, L, and N_1 are constant. Hence, the input voltage for the x axis channel is proportional to the auxiliary magnetic field H.

If the cross-sectional area of the sample is S, then according to the law of electromagnetic induction, the induced electromotive force in a secondary coil with the number of turns N_2, is

$$\varepsilon_2 = -N_2 S \frac{\mathrm{d}B}{\mathrm{d}t} \tag{1}$$

Assuming that the number of turns N_2 in the secondary coil is small, the electromotive force due to self-induction can be ignored. Moreover, if the values of the resistance R_2 and the capacitance C are chosen so that $R_2 \gg 1/\varepsilon C$, then

$$\varepsilon_2 = R_2 i_2 \tag{2}$$

Substituting $i_2 = \frac{\mathrm{d}q}{\mathrm{d}t} = C\frac{\mathrm{d}U_c}{\mathrm{d}t}$ into Eq. (2) and combining with Eq.(1) one obtains

$$U_C = -\frac{N_2 S B}{R_2 C}$$

which shows that the input voltage U_C for the y axis channel is proportional to the magnetic field B.

2.4 Measurement of the Curie Temperature with an Alternating Current Bridge

An alternating-current (AC) bridge can be used to measure the Curie temperature of a ferromagnetic material. Although there are many variations of AC bridges, such as the Maxwell bridge, the Owen bridge, etc, the basic working principle can be illustrated with a four-side impedance bridge as shown in Figure 4.

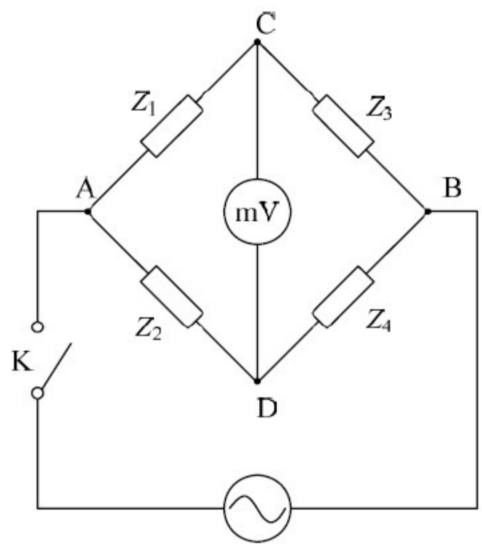

Figure 4: Four-side impedance bridge.

The four sides of the bridge are combinations of resistive, capacitive, and inductive elements combined in series or in parallel. The idea is to adjust the parameters of the bridge in order to eliminate a potential difference between the points C and D. When the bridge reaches this equilibrium state, one should have

$$\frac{Z_1}{Z_2} = \frac{Z_3}{Z_4}$$

To make this equality hold, the moduli and the phases of both sides should be equal,*i.e.*

$$\frac{|Z_1|}{|Z_2|} = \frac{|Z_3|}{|Z_4|}, \varphi_1 + \varphi_4 = \varphi_2 + \varphi_3$$

respectively. Then the bridge is balanced, *i.e.* the potential difference between the points C and D is equal to zero.

Figure 5 shows a RL AC bridge used in this experiment. The input current source is supplied by a signal generator, allowing to chose a suitable (high) output frequency. The elements Z_1 and Z_2 are resistors, whereas Z_3 and Z_4 are inductors with a finite resistance r_1 and r_2, respectively. The impedances of these four elements are

$$Z_1 = R_1, Z_2 = R_2, Z_3 = r_1 + j\omega L_1, Z_4 = r_2 + j\omega L_2$$

with j being the imaginary unit ($j^2 = -1$) and ω the angular frequency of the signal provided by the voltage source. When the bridge is in balance

$$r_2 = \frac{R_2}{R_1} r_1, L_2 = \frac{R_2}{R_1} L_1$$

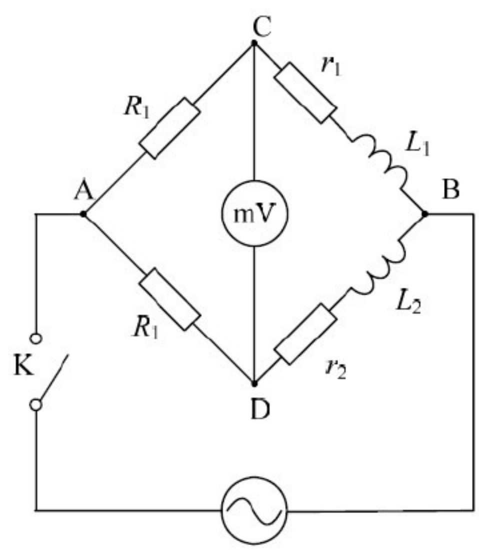

Figure 5: AC bridge

First, the AC bridge with the ferromagnetic sample removed needs to be balanced by adjusting parameters of the circuit components. After the sample is placed in the apparatus, the balance will be broken because of the resulting change in the inductance. Then, when the temperature is increased to the critical value, the ferromagnet undergoes a transition to the paramagnetic state, the potential difference between C and D will suddenly becomes nearly zero again and at this very point the balance is recovered. This particular transition point allows one to estimate the Curie temperature, *i.e.* the temperature of the ferromagnetic-paramagnetic phase transition, by observing the voltage-temperature curve.

In this exercise, the right half ($r1, L1, r2$ and $L2$) of the AC bridge, along with the temperature probe, is placed in a glass vacuum-tube heating pipe. Heating is provided by a voltage/current source and Series voltage sources mode should be chosen. The tube should be heated starting from the room temperature to about $60^{o}C$ by using moderate values of the voltage (about 7 V each, obtained from the test). It is important to wait for the system to reach a thermal balance (waiting time is about 5 minutes), and then gradually increase the input voltage so that the temperature rises slowly enough (that is the value of U_{CD} does not change too fast). If the heating process is too fast, the temperature probe and the sample will have different temperatures, resulting in an inaccurate measurement. This is especially important when the temperature gets close to the Curie temperature; the measurement will be inaccurate if the voltage U_{CD} is not changing slowly enough.

3 Apparatus

The apparatus for this exercise consists of the following main elements: a signal generator, an oscilloscope, a digital multimeter, a platinum resistance thermometer, a glass vacuum-tube heating pipe, a voltage/current source, a wiring block, a capacitor, two 200Ω resistors, a 10Ω resistor, a 2.2 kΩ variable resistor, and a 1kΩ resistor (the actual values of the resistance should be measured during the session). Ferromagnetic samples will be provided by the instructor.

The parameters of other elements are: $L = 3.61 \cdot 10^{-2}$m, $S = 1.25 \cdot 10^{-5}\text{m}^2$ and $N_1 = N_2 = 100$. The capacity is indicated on the capacitor.

4 Procedure

4.1 Magnetic Hysteresis Loop Measurement

1. Assemble the circuit according to Figure 3 with the signal source disconnected.

2. Turn on the signal source and adjust the frequency to 1 kHz or above. Keep in mind that you must not short the signal source, or set the frequency below 1 kHz (otherwise the equipment will be damaged).

3. Connect the signal source to the circuit and observe the U_{R_1} vs. U_C loop under different conditions:

   (1) with different signal frequencies (1∼2 kHz) and amplitudes (1∼5 V),

   (2) with different values of the resistance R_2.

4. Obtain the saturated hysteresis loop for a certain frequency (1∼2 kHz) and suitable value of the resistance R_2 (about 1 kΩ); shift the picture of the loop to the center of the oscilloscope screen, adjust its size and show the visualization to the instructor.

5. Trace the whole loop with no less than 16 points (see Figure 2 for the location of the points).

6. Turn off the signal source, disconnect the circuit and measure the resistances.

7. After class, plot the magnetic hysteresis loop (HB loop), and find $\pm B_r, \pm H_c, \pm B_s, \pm H_s$.

4.2 Measurement of the Curie Temperature with an AC Bridge

1. Properly set the AC measurement range on the multimeter and assemble the circuit according to Figure 5.

2. A small piece of the ferromagnetic sample will be provided by the instructor. Study the circuit without heating up the sample. Note the differences before and after placing the ferromagnetic sample in the coil.

3. Put the right half of the AC bridge (two coils, one of the coils should contain the ferromagnetic sample) into the heating pipe. Set the voltage/current source in the Series mode to heat up the tube. Adjust the voltages to 7 V each and wait for about 5 minutes for the thermal balance at about 60^{o}C (approximate value; may differ due to the changes in the room temperature and different resistances of the heaters). Record T vs. U_{CD} with intervals of about 5^{o}C during this step if U_{CD} is not changing too fast.

4. After the first thermal balance is reached, slightly increase the voltage of the sources by about 0:5 V each. Above 60^{o}C, record T vs. U_{CD} with intervals of about 0.1^{o}C and make sure that U_{CD} is not changing too fast. Continue recording until the thermal balance is reached again.

5. Repeat Step 4 several times until the change of U_{CD} with T is sufficiently small (above ca. 80^{o}C).

6. Disconnect the circuit, wait for the tube to cool down and remove the coils from the pipe; return the ferromagnetic sample to the instructor.

7. After class, use a computer to plot the U_{CD} vs. T curve and the $\triangle U_{CD} = \triangle T$ vs. T curve to identify the Curie temperature (as the temperature for which the ratio$\triangle U_{CD} = \triangle T$ is minimum).

5 Results and Calculation

5.1 Parameters of Circuit Components

N_1	100
N_2	100
R_1	$10.78 \pm 0.01[\Omega]$
R_2	$219.49 \pm 0.01[\Omega]$
L	$3.61 \times 10^{-2} \pm 0.01 \times 10^{-2}[m]$
S	$1.25 \times 10^{-5} \pm 0.01 \times 10^{-5}[m^2]$
C	$4.345 \pm 0.001[\mu F]$

Table 1: Parameters of circuit components

5.2 Oscilloscope-measured values of U_{R_1} and U_C

$U_{R_1}(\pm 0.001[V])$	$U_C(\pm 0.001[V])$
-0.350	-0.650
-0.250	0.000
-0.000	0.600
0.320	0.800
0.190	0.000
0.000	-0.410
-0.290	-0.500
-0.100	0.500
0.240	0.500
-0.130	-0.500
0.170	-0.120
-0.270	-0.120
-0.210	0.290
0.220	0.290
-0.020	0.580
0.240	0.580

Table 2: Oscilloscope-measured values of U_{R_1} and U_C in the circuit

5.3 Calculation of B and H

$$H_1 = \frac{U_{R_1} N_1}{R_1 L} = \frac{-0.350 \times 100}{10.78 \times 3.61 \times 10^{-2}} = -89.9[A/m]$$

$$B_1 = -\frac{U_c R_2 C}{N_2 S} = -\frac{-0.650 \times 219.49 \times 4.345}{100 \times 1.25 \times 10^{-5}} = 0.496[A/m]$$

$H[A/m]$	$B[A/m]$
-89.9	0.496
-64.2	0.000
0.00	-0.458
82.2	-0.610
48.8	0.000
0.00	0.313
-74.5	0.381
-25.7	-0.381
61.7	-0.381
-33.4	0.381
43.7	0.0916
-69.4	0.0916
-54.0	-0.221
56.5	-0.221
-5.14	0.443
61.7	0.443

Table 3: Oscilloscope-measured values of U_{R_1} and U_C in the circuit

6 Uncertainty Analysis

6.1 Uncertainty of H

$$u_H = \sqrt{(\frac{\partial B}{\partial U_u} u_u)^2 + (\frac{\partial H}{\partial R_1} u_R)^2 + (\frac{\partial H}{\partial L} u_L)^2}$$

$$\sqrt{(\frac{100}{10.78 \cdot 3.61} \cdot 10^{-1})^2 + (\frac{0.35 \cdot 100}{(10.78)^2 \cdot 3.61})^2 + (\frac{0.35 \cdot 100}{10.78 \cdot (3.61)^2})^2}$$

$$u_H = 9.6 \cdot 10^{-2}, u_r = \frac{u_H}{H} \cdot 100\% = 0.11\%$$

$$H_1 = -89.9 \pm 9.6 \cdot 10^{-2} [A/m]$$

$H[A/m]$	$u_H[A/m]$	$u_r\%$
-89.9	$9.6 \cdot 10^{-2}$	0.11%
-64.2	$5.3 \cdot 10^{-2}$	0.08%
0.00	$6.6 \cdot 10^{-2}$	0.00%
82.2	$9.3 \cdot 10^{-2}$	0.11%
48.8	$8.1 \cdot 10^{-2}$	0.17%
0.00	$6.6 \cdot 10^{-2}$	0.00%
-74.5	$5.2 \cdot 10^{-2}$	0.07%
-25.7	$6.0 \cdot 10^{-2}$	0.23%
61.7	$8.5 \cdot 10^{-2}$	0.14%
-33.4	$7.6 \cdot 10^{-2}$	0.23%
43.7	$7.9 \cdot 10^{-2}$	0.18%
-69.4	$8.8 \cdot 10^{-2}$	0.13%
-54.0	$8.2 \cdot 10^{-2}$	0.15%
56.5	$8.3 \cdot 10^{-2}$	0.15%
-5.14	$6.7 \cdot 10^{-2}$	1.30%
61.7	$8.5 \cdot 10^{-2}$	0.14%

Table 4: Uncertainty of H

6.2 Uncertainty of B

$$u_B = \sqrt{(\frac{\partial B}{\partial U_c}u_u)^2 + (\frac{\partial B}{\partial R_2}u_R)^2 + (\frac{\partial B}{\partial C}u_c)^2 + (\frac{\partial B}{\partial s}u_s)^2}$$

$$\sqrt{(\frac{219.49 \cdot 4.345 \cdot 10^{-6}}{1.25})^2 + (\frac{0.65 \cdot 4.345 \cdot 10^{-5}}{1.25})^2 + (\frac{0.65 \cdot 219.49}{1.25} \cdot 10^{-6})^2 + (\frac{0.65 \cdot 219.49 \cdot 4.345}{(1.25)^2} \cdot 10^{-5})^2}$$

$$u_B = 4.04 \cdot 10^{-3}, u_r = \frac{u_B}{B} \cdot 100\% = 0.81\%$$

$$B_1 = 0.496 \pm 4.04 \cdot 10^{-3}[A/m]$$

$B[A/m]$	$u_B[A/m]$	$u_r\%$
0.496	$4.0 \cdot 10^{-3}$	0.81%
0.000	$0.8 \cdot 10^{-3}$	0.00%
-0.458	$3.7 \cdot 10^{-3}$	0.81%
-0.610	$4.9 \cdot 10^{-3}$	0.80%
0.000	$0.8 \cdot 10^{-3}$	0.00%
0.313	$2.6 \cdot 10^{-3}$	0.83%
0.381	$2.4 \cdot 10^{-3}$	0.63%
-0.381	$2.4 \cdot 10^{-3}$	0.63%
-0.381	$2.4 \cdot 10^{-3}$	0.63%
0.381	$2.4 \cdot 10^{-3}$	0.63%
0.0916	$1.1 \cdot 10^{-3}$	1.2%
0.0916	$1.1 \cdot 10^{-3}$	1.2%
-0.221	$1.9 \cdot 10^{-3}$	0.86%
-0.221	$1.9 \cdot 10^{-3}$	0.86%
0.443	$3.6 \cdot 10^{-3}$	0.81%
0.443	$3.6 \cdot 10^{-3}$	0.81%

Table 5: Uncertainty of B

6.3 Plot of B vs. H

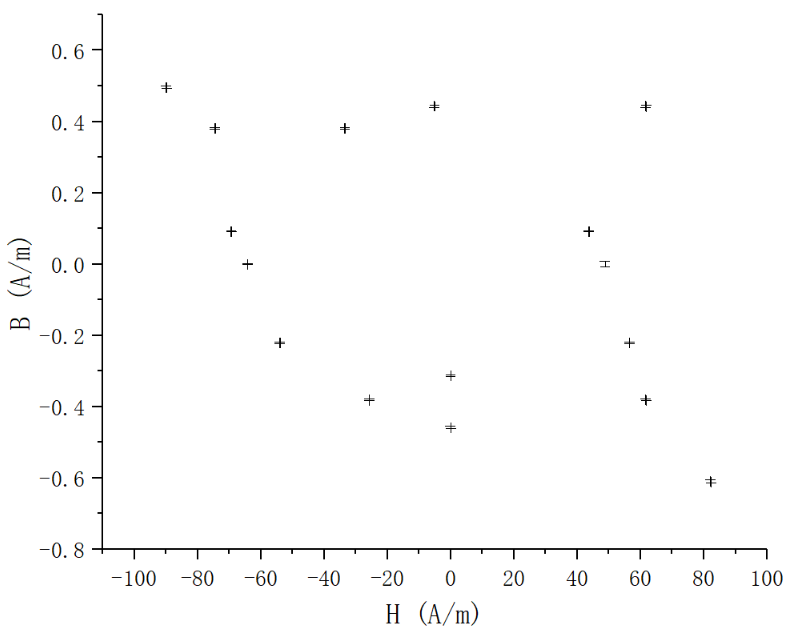

Figure 6: Plot of B vs. H

quantity	$[A/m]$	$u[A/m]$	$u_r[\%]$
B_s	0.496	$4.0 \cdot 10^{-3}$	0.81%
$-B_s$	-0.610	$4.9 \cdot 10^{-3}$	0.80%
H_s	-89.9	$9.6 \cdot 10^{-2}$	0.11%
$-H_s$	82.2	$9.3 \cdot 10^{-2}$	0.11%
H_c	-64.2	$5.3 \cdot 10^{-2}$	0.08%
$-H_c$	48.8	$8.1 \cdot 10^{-2}$	0.17%
B_r	0.313	$3.9 \cdot 10^{-3}$	0.81%
$-B_r$	-0.458	$2.6 \cdot 10^{-3}$	0.83%

Table 6: Data for $\pm B_s, \pm H_s, \pm H_c, \pm B_r$

7 Conclusion

Through this lab work, I have a rough idea about basic characteristic of magnetic materials. I become familiar with paramagnetic and ferromagnetic materials. I know the magnetic hysteresis loop, a distinct characteristic of ferromagnetic materials.

In this experiment, I built a circuit to measure B and H indirectly by measure the voltage of the capacitor and resistor, then make a plot of B and H. My plot is opposite to the figure in lab manual, I think it's because $U_C = -\frac{N_2SB}{R_2C}$, which makes the figure is opposite to the picture on the oscilloscope.

In the second part of the experiment, we're asked to measure the Curie Temperature by building the four-side impedance bridge. But, we didn't do it due to the time limit but I still learn a lot of thing about the Curie Temperature of ferromagnetic materials.

7.1 Error Analysis

The relative uncertainty is not very big, but it becomes bigger as B and H becomes smaller. In addition, my plot is not symmetric enough, I think the error is caused by the oscilloscope. When I use the oscilloscope, I put the center of the graph at the center of the monitor but after I start measuring, it moved away, so the whole graph was changed.

7.2 Improvement

1. I should measure more value of B and H next time because I measured too much points with same B and H, which may cause more error.

2. When I use the Oscilloscope next time, I should pay more attention to the position of the figure to make sure I get the correct picture.

8 Data Sheet

Data sheet is attach to the report

9 Reference

Young, H.D., Freedman R.A. University Physics. Chapter 28,31.
Krzyzosiak,M. Lab Manual of Exercise 1.
Qin Tian, Zeng Ming, Zhao Xijian, Krzyzosiak,M. Handbook-Uncertainty Analysis.