UM–SJTU Joint Institute

Physics Laboratory
(VP241)

Laboratory Report

Exercise 1
Basic Characteristics of Magnetic Materials

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Date: 18 Nov 2016

[rev. 1.0]

Contents

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 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 dis- cussed 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 magnetically 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 $\mu_r = \chi_m + 1 = B = /\mu_0$ 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 $\mu_r \gg 1$.

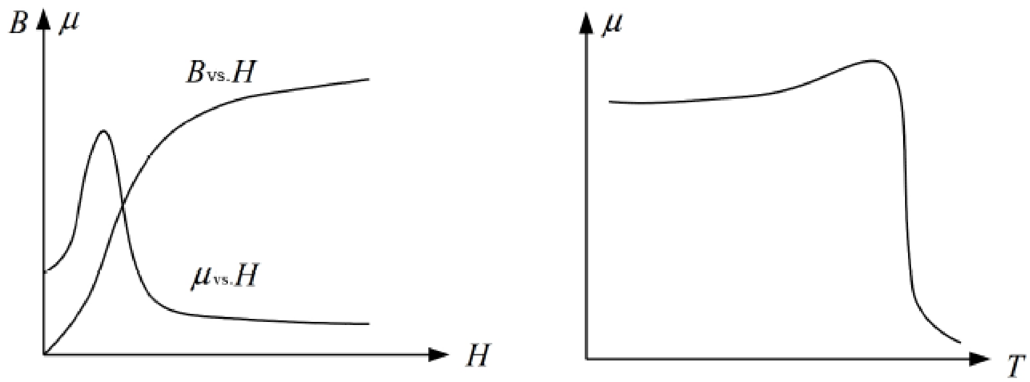

Figure 1: (left) The magnetization curve B(H) for a ferromagnetic material and the curve μ(H). (right) A generic graph of the μ(T) curve for a ferromagnetic material.

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 = μH. How- ever, 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

eld 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 $-H_S$, 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.

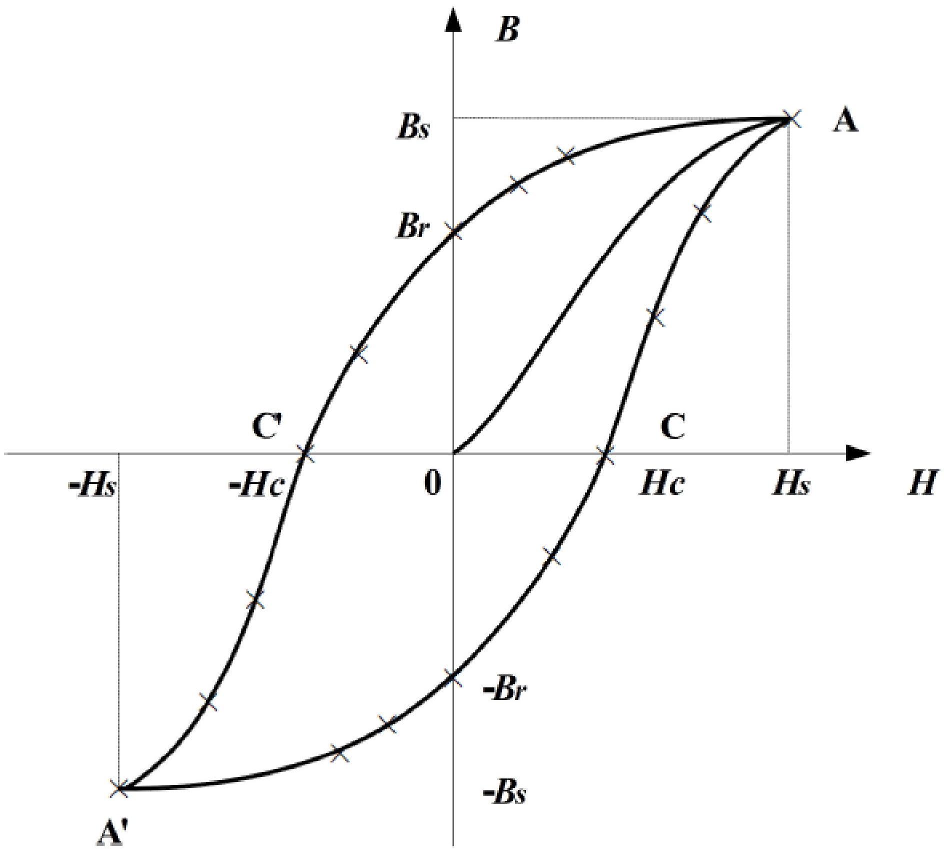

Figure 2: The magnetization curve and the magnetic hysteresis loop of a ferromagnetic material. The crosses indicate the points to be recorded to describe the loop.

2.3 Visualization on the Oscilloscope

Figure 3 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 Ampere'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

$$\varepsilon_2 = -N_2 S \frac{dB}{dt} \tag{1}$$

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 $R2 \gg 1/\omega C$, then

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

Substituting $i_2 = dq/dt = C dU_C/dt$ into Eq. (2) and combining with Eq. (1) one obtains

$$U_C = -\frac{N_2 SB}{R_2 C} \tag{3}$$

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

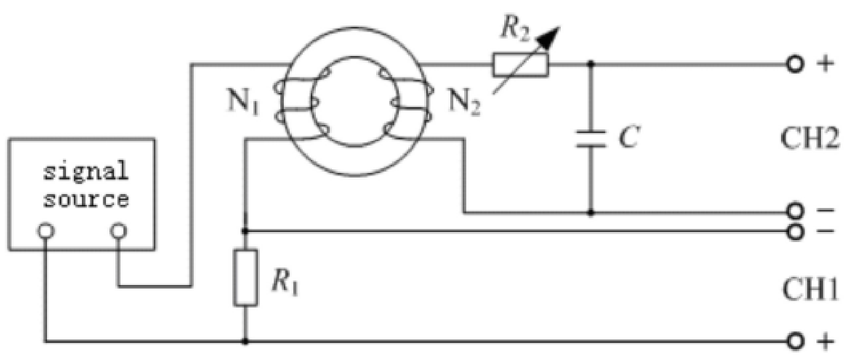

Figure 3: The electric circuit for visualization of the magnetization curve and the magnetic hysteresis loop on the oscilloscope. $R_1 = 10\Omega$ and R_2 is a variable resistor with maximum resistance of $2.2k\Omega$.

3 Measurement Setup and Procedure

3.1 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 2.2kΩ variable resistor, and a 1 kΩ 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: $L = 3.61 \times 10^{-2} m$, $S = 1.25 \times 10^{-5} m^2$ and $N_1 = N_2 = 100$. The capacity is indicated on the capacitor.

3.2 Measurement Procedure

3.2.1 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:

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

   (2) with different values of the resistance R_2.

5. 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.

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

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

8. After class, plot the magnetic hysteresis loop (H-B loop), and find $\pm B_r$, $\pm H_c$, $\pm B_s$, $\pm H_s$.

4 Results

4.1 Magnetic Hysteresis Loop Measurement

N_1	100
N_2	100
R_1	10.17 ± 0.01 [Ω]
R_2	992.9 ± 0.1 [Ω]
L	$3.61 \times 10^{-2} \pm 10^{-4}$ [m]
S	$1.25 \times 10^{-5} \pm 1-^{-7}$ [m^2]
C	4.334 ± 0.001 [μF]

Table 1: Parameters of circuit components (cf. Figure 3).

$U_{R_1}(\pm 0.5\ [mV])$	-213.0	-150.0	-100.0	-50.0	0.0	50.0
$U_C(\pm 0.5\ [mV])$	139.0	131.5	123.0	110.0	90.0	53.0
$U_{R_1}(\pm 0.5\ [mV])$	72.5	100.0	150.0	212.0	150.0	100.0
$U_C(\pm 0.5\ [mV])$	0.0	-80.5	-116.5	-134.0	-127.5	-118.0
$U_{R_1}(\pm 0.5\ [mV])$	50.0	0.0	-44.5	-101.0	-91.0	-150.0
$U_C(\pm 0.5\ [mV])$	-104.5	-82.5	-43.5	0.0	84.5	121.0

Table 2: Oscilloscope measured values of U_{R_1} and U_C in the circuit illustrated in Figure 3.

The data of H and B was calculated and shown in Table 3.

No	H [T]	B [1×10^3 T]
1	-58.02 ± 0.22	-478.52 ± 4.20
2	-40.86 ± 0.18	-452.70 ± 4.01
3	-27.24 ± 0.16	-423.44 ± 3.80
4	-13.62 ± 0.14	-378.68 ± 3.49
5	0.00 ± 0.14	-309.83 ± 3.02
6	13.62 ± 0.14	-182.46 ± 2.26
7	19.75 ± 0.15	-0.00 ± 1.72
8	27.24 ± 0.16	277.13 ± 2.81
9	40.86 ± 0.18	401.06 ± 3.64
10	57.74 ± 0.22	461.31 ± 4.07
11	40.86 ± 0.18	438.93 ± 3.91
12	27.24 ± 0.16	406.22 ± 3.68
13	13.62 ± 0.14	359.75 ± 3.35
14	0.00 ± 0.14	284.01 ± 2.85
15	-12.12 ± 0.14	149.75 ± 2.10
16	-16.62 ± 0.14	-0.00 ± 1.72
17	-24.79 ± 0.15	-290.90 ± 2.90
18	-40.86 ± 0.18	-416.55 ± 3.75

Table 3: The data of H and B.

The figure was plotted in Figure 4.

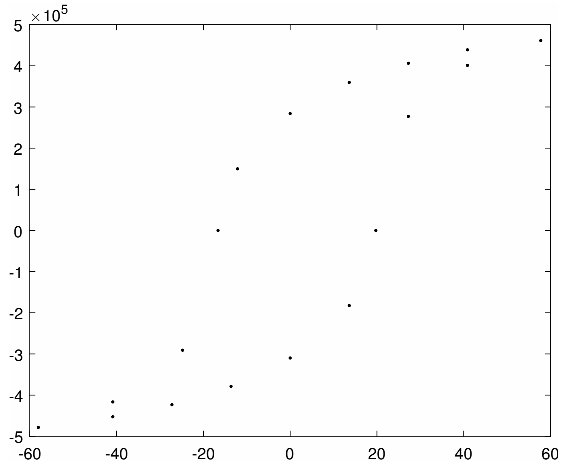

Figure 4: H vs. B graph.

5 Measurement uncertainty analysis

5.1 Relation Between Sensitivity K_H and Working Voltage U_S

H can be calculated by the equation $H = \frac{N_1 U_{R_1}}{R_1 L}$. Therefore its uncertainty u_H is found by applying the uncertainty propagation formula

$$\begin{aligned} u_H &= \sqrt{\left(\frac{\partial H}{\partial U_{R_1}}\right)^2 u_{U_{R_1}}^2 + \left(\frac{\partial H}{\partial R_1}\right)^2 u_{R_1}^2 + \left(\frac{\partial H}{\partial L}\right)^2 u_L^2} \\ &= N_1 \sqrt{\left(\frac{1}{R_1 L}\right)^2 u_{U_{R_1}}^2 + \left(\frac{U_{R_1}}{R_1^2 L}\right)^2 u_{R_1}^2 + \left(\frac{U_{R_1}}{R_1 L^2}\right)^2 u_L^2} \end{aligned}$$

B can be calculated by the equation $B = -\frac{R_2 C U_C}{N_2 S}$. Therefore its uncertainty u_B is found by applying the uncertainty propagation formula

$$\begin{aligned} u_B &= \sqrt{\left(\frac{\partial B}{\partial R_2}\right)^2 u_{R_2}^2 + \left(\frac{\partial B}{\partial C}\right)^2 u_C^2 + \left(\frac{\partial B}{\partial U_C}\right)^2 u_{U_C}^2 + \left(\frac{\partial B}{\partial S}\right)^2 u_S^2} \\ &= \frac{1}{N_2} \sqrt{\left(\frac{C U_C}{S}\right)^2 u_{R_2}^2 + \left(\frac{R_2 U_C}{S}\right)^2 u_C^2 + \left(\frac{R_2 C}{S}\right)^2 u_{U_C}^2 + \left(\frac{R_2 C U_C}{S^2}\right)^2 u_S^2} \end{aligned}$$

6 Conclusion

In this lab, I studied the shape of the magnetic hysteresis loop and the magnetization curve, and understand how to use these characteristics to discuss properties of ferromagnetic materials.

According to the two equations

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

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

We can get the linear relationship between the value we measured on the oscilloscope and the real strength of magnetic fields.

7 Reference

(a) Qin Tian, Zeng Ming, Mateusz Krzyzosiak, VP241 Exercise 1, Basic Characteristics of Magnetic Materials, based on materials provided by the Department of Physics, Shanghai Jiaotong University.

8 Data sheet

The Data sheet is attached at the end of the report.