CHALMERS UNIVERSITY OF TECHNOLOGY
GÖTEBORG UNIVERSITY

EM4: Magnetic Hysteresis

– Lab manual –
(version 1.001a)

Students: .... & ....

Date: .... / .... / ....

Laboration passed: ....

Supervisor: .... **Date:** .... / .... / ....

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Aims:

In this laboratory session you will learn about the basic principles of magnetic hysteresis; learn about the properties of ferromagnetic materials and determine their dissipation energy of remagnetization.

Questions:

(Please answer on the following questions before coming to the laboratory)

1) What classes of magnetic materials do you know?
2) What is a 'magnetic domain'?
3) What is a 'magnetic permeability' and 'relative permeability'?
4) What is a 'hysteresis loop' and how it can be recorded? (How you can measure a magnetization and magnetic field indirectly?)
5) What is a 'saturation point' and 'magnetization curve' for a hysteresis loop?
6) How one can demagnetize a ferromagnet?
7) What is the energy dissipation in one full hysteresis loop and how it can be calculated from an experiment?

Equipment list:

1 Sensor-CASSY
1 U-core with yoke
2 Coils (N = 500 turnes, L = 2,2 mH)
1 Clamping device
1 Function generator S12
2 12 V DC power supplies
1 STE resistor 1Ω, 2W
1 Socket board section
1 Connecting lead, 50 cm
7 Connecting leads, 100 cm
1 PC with Windows 98 and CASSY Lab software

Introduction

In general, term “hysteresis” (comes from Greek “hystérësis”, - lag, delay) means that value describing some physical process is ambiguously dependent on an external parameter and antecedent history of that value must be taken into account. The term was added to the vocabulary of physical science by J. A. Ewing, who defined it as following: “When there are two quantities M and N such that cyclic variations of N cause cyclic variations of M, then if the changes of M lag behind those of N, we may say that there is hysteresis in the relation of M to N” [1]. One can meet the word ”hysteresis” in magnetism and electricity, thermodynamics, where it is always a sign of first-order phase transition.

Magnetic hysteresis

Ferromagnetism

Iron, nickel, cobalt and some of the rare earths (gadolinium, dysprosium) exhibit a unique magnetic behavior which is called ferromagnetism (iron or ‘ferric’ is the most common and most dramatic example of a ferromagnetic material). Ferromagnetic materials exhibit a long-range ordering phenomenon at the atomic level which causes the atomic magnetic moments to line up parallel with each other in a region called a domain. Within the domain, the magnetization is intense, but in a bulk sample the material will usually be demagnetized because the many domains will be randomly oriented with respect to one another. A small externally imposed magnetic field, say from a solenoid, can cause the magnetic domains to line up with each other. The magnetic flux density in the material will then be increased by a large factor called relative permeability for the material compared to the magnetic flux density in vacuum, $\mu_0 H$. All ferromagnets have a maximum temperature where the ferromagnetic property disappears as a result of thermal agitation. This temperature is called the Curie temperature.

Hysteresis loop

When a ferromagnetic material is magnetized in one direction, it will not relax back to zero magnetization when the imposed magnetizing field is removed. It must be driven back to zero by a field in the opposite direction. If an alternating magnetic field is applied to the material, its magnetization will trace out a loop called a hysteresis loop (see Figure 1). The lack of retraceability of the magnetization curve is the property called hysteresis and it is related to the existence of magnetic domains in the material. Once the magnetic domains are reoriented, it takes some energy to turn them

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[1] Phil. Trans., 1885, 176, p. 524

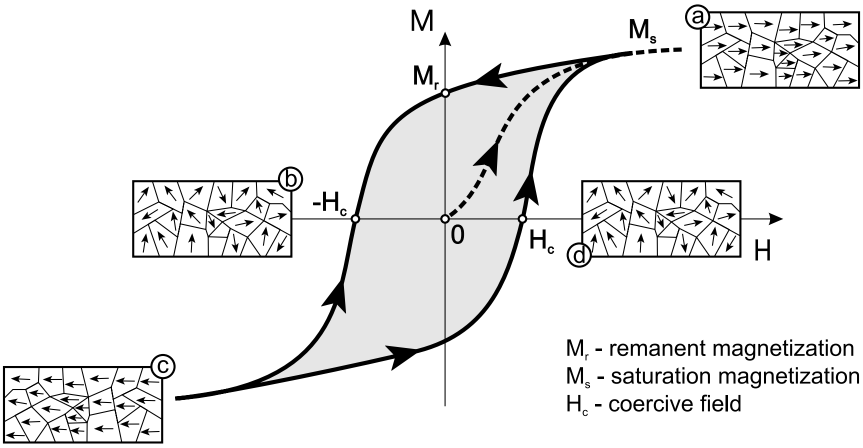


Figure 1: The magnetization 'M' vs magnetic field strength 'H' for a ferromagnetic:
(a) starting at zero the material follows at first a non-linear magnetization curve and reaches the saturation level , when all the magnetic domains are aligned with the direction of a field; when afterwards driving magnetic field drops to zero, the ferromagnetic material retains a considerable degree of magnetization or "remember" the previous state of magnetization;
(b) at this point, when H = 0 a ferromagnet is not fully demagnetized and only the partial domain reorientation happened;
(c) saturation level in the opposite direction of applied field;
(d) in order to demagnetize a ferromagnetic material the strong magnetic field of the opposite direction (called "coercive field, 'H_c') has to be applied.

back again. This property of ferromagnetic materials is useful as a magnetic "memory". Some compositions of ferromagnetic materials will retain an imposed magnetization indefinitely and are useful as "permanent magnets". The magnetic memory aspects of iron and chromium oxides make them useful in audio tape recording and for the magnetic storage of data on computer disks.

Basic relations of magnetic hysteresis theory

In vacuum the generated magnetic flux density or magnetic induction is proportional to applied field B:

$$\mathbf{B} = \mu_0 \mathbf{H}, \tag{1}$$

where $\mu_0 = 4\pi \cdot 10^{-7} Vs/Am = 1,26 \cdot 10^{-6} Vs/Am$. The units of the magnetic field are A/m and for the magnetic flux density $\mathbf{B}$ we have $Vs/m^2 = 1$ Tesla.

If material is present, this equation becomes

$$\mathbf{B} = \mu_{\mathrm{r}}\mu_0\mathbf{H}, \tag{2}$$

with μ_r - relative permeability of the material. The relative permeability of the material is dimensionless and is a pure number characterizing the material. It is useful and conventional to split $\mathbf{B}$ into the flux density in vacuum plus the “part of the material” according to

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}), \tag{3}$$

where $\mathbf{M}$ is magnetization (total magnetic moment) vector that is only material dependent. While excluding $\mathbf{B}$ from the equation (3) one can obtain

$$\mathbf{M} = (\mu_{\mathrm{r}} - 1)\mathbf{H}. \tag{4}$$

The relative permeability μ_r is the prime material parameter we are after. It describes the response of a material to a magnetic field.

If a ferromagnetic material is chosen one can observe that a generated magnetic flux density in the material is not proportional to applied field $\mathbf{H}$. Rather, it reaches a saturation value B_s as the magnetic field $\mathbf{H}$ increases. The relative permeability μ_r of the ferromagnet depends on the magnetic field strength $\mathbf{H}$, and also on the previous magnetic treatment of the ferromagnet. In a demagnetized ferromagnet, the magnetic field strength is $\mathbf{B} = 0$ T at $\mathbf{H} = 0$ A/m. Normally however, a ferromagnet still retains a residual magnetic flux density $\mathbf{B}$ not equal to 0 T when $\mathbf{H} = 0$ A/m (remanence) or remembers its previous state . Thus, the hysteresis curve differs from the magnetization curve, which begins at the origin of the coordinate system and can only be measured for completely demagnetized material $(\mathbf{H} = 0\ \mathrm{A/m}, \mathbf{B} = 0\ \mathrm{T})$.

The values of magnetic field strength and magnetic induction can be measured indirectly by monitoring the applied current I in the transformer coil and the induced magnetic flux Φ through the core and taking into account the relations

$$H = \frac{N_1}{L}I, \qquad B = \frac{\Phi}{N_2 A}, \tag{5}$$

where N_1, N_2 are the number of turns in primary and secondary coils respectively, L is the inductance of a coil, A is the cross-section of a ferromagnet. The magnetic flux Φ is calculated as the integral of the voltage U_s induced in the secondary coil.

The area of a hysteresis loop $B(H)$

$$\int BdH = \frac{E}{V} \tag{6}$$

just corresponds to the energy density loss in remagnetization of the demagnetized material. The enclosed area in the diagram $\Phi(I)$

$$\int \Phi dI = \int N_2 AB \frac{L}{N_1} dH = \frac{N_1}{N_2} V \int BdH = \frac{N_2}{N_1} E \tag{7}$$

gives the precisely energy loss E of the remagnetization for $N_1 = N_2$.

Experimental

In this laboratory work the phenomenon of magnetic hysteresis is explored by means of scanning the magnetic field through the transformer core (made of soft iron ferromagnet) and recording the magnetization dependence on the applied magnetic field.

Set-up

Using the equipment listed above build the experimental set-up by coupling the equipment parts with each other according to the Figure 2.

Notes:

a) both the function generator and the sensor CASSY have to be supplied with 12 V external DC power source, that you can find among the listed equipment;
b) check the connection once again before switching ON power supplies and turning the knobs.

The settings on the function generator S12 have to be as following: output signal to sawtooth shape “/\/\/\”, frequency around 0.1 Hz and amplitude about 1 - 2 V (1 V is recommended). Recording of the magnetization curve is triggered at I = 0 A (when current I changes its sign from “-” to “+”). To hit this point exactly, the current is shunted past the transformer by the relay and flows through the 1 Ω resistor prior to recording of the curve.

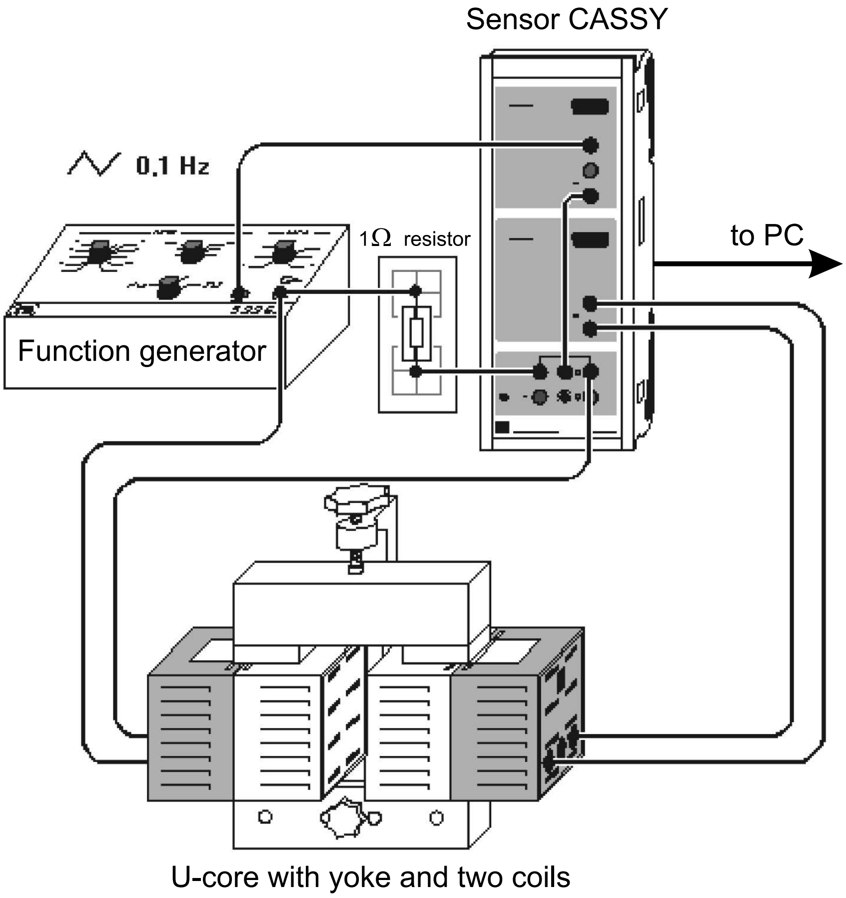


Figure 2: The CASSY Hysteresis Lab (without POWER-CASSY) experimental set-up.

Carrying out the experiment

• load the CASSY Hysteresis Lab by double clicking on the corresponding icon on Windows desktop;
• correct the offset for U_B if necessarily: open Settings U_B, select **Correct**, set the first target value to '0 V' and click **Correct Offset**;
• demagnetize the transformer core, e.g. by striking the end face of the yoke against the end faces of the U-core several times;
• start the measurement with **F9**;
• stop the measurement with **F9** after one period of the hysteresis curve or at F = 0 Vs (in this case the core does not have to be demagnetized again);
• achieve the 'nice' hysteresis loop diagram: magnetization curve should start from the zero position and the hysteresis loop should be symmetrically positioned in the center; save the data;

Hints:

- while demagnetizing the core by striking the end face of the yoke against the end faces of the U-core one should do it when the measurements is stopped, so that the current is passing through the resistor instead of going through the coil. It is recommended also not to switch voltage on functional generator OFF at this point, because it can trigger automatically the relay (inside of the Sensor-CASSY) in the coil position when one will turn the voltage back ON, so that the current will flow through the primary coil which makes you work on demagnetization vain;
- if the hysteresis curve lies in the second and fourth quadrants, reverse the connections on one of the two coils;
- if the display instrument U$_B$ is overdriven during measurement (display flashes), extend the measuring range in Settings U$_B$.

Tasks:

1) record a nice hysteresis loop for a soft iron core material as $\Phi(I)$ dependence;
2) calculate the area of the hysteresis loop by using the **peak integration** function (the value of the integral will appear in the left bottom corner); what is the energy loss of the remagnetization?
3) make a transformation of the recorded dependence $\Phi(I) \rightarrow B(H) \rightarrow M(H)$; plot the dependencies $\Phi(I)$, $B(H)$ and $M(H)$;
4) calculate from the obtained hysteresis loops the values of remanent magnetization M_r, coercive field H_c, saturation magnetization M_s and relative permeability μ_r (in a weak field region) of the soft iron ferromagnet;
5) what type (slope and area) of hysteresis curve $M(H)$ would you like to have for: a) transformer core; b) permanent magnet; c) memory element; explain your choice.
6) insert the printed dependencies into the report; write down the answers on the question 2, 4 and 5 in the corresponding graphs below and submit the report to the supervisor.

$<< \Phi(I) dependence >>$

Energy loss of remagnetization $E =$ .... , [units] = ...

Answer here:

$<< B(H) dependence >>$

Relative permeability $\mu_r =$ .... , [units] = ...

Answer here:

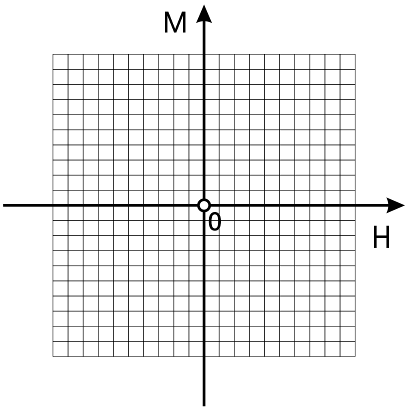
$<< M(H) dependence >>$

Remanent magnetization $M_r =$ .... , [units] = ...

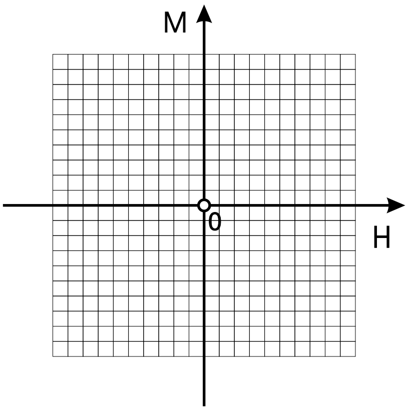
Coercive force $H_c =$ .... , [units] = ...

Saturation magnetization $M_s =$ .... , [units] = ...

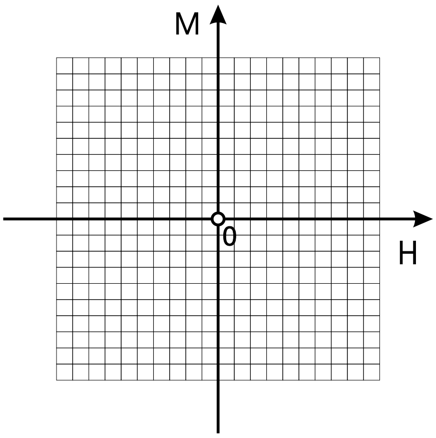
What type (slope and area) of hysteresis curve $M(H)$ would you like to have for (draw the hysteresis loops in each graph):



a) transformer core



b) permanent magnet



c) memory element

Explain your choice: .....