G1. Magnetic Hysteresis Cycle

I. OBJECTIVE OF THE EXPERIMENT

Magnetic materials are very important in technological fields, and have many different uses. The objective of the experiment is to study a few of their properties, specifically the hysteresis cycle, and values attached to it.

II. PHENOMENOLOGY

1. Magnetism in matter

The magnetic state of a material can be described by a vector $\vec{M}$ called magnetization, or dipolar magnetic moment per unit volume. In a vacuum, the *magnetic induction* $\vec{B}$ and the magnetic field $\vec{H}$ are connected by the equation:

$$\vec{B} = \mu_0 \vec{H}$$

where $\mu_0 = 4\pi \cdot 10^{-7} \frac{\mathrm{Vs}}{Am}$ is the absolute magnetic permeability in a vacuum

However, in matter, magnetic induction depends on magnetization $\vec{M}$ in the following way:

$$\vec{B} = \mu_o \vec{H} + \vec{M}$$

Magnetization $\vec{M}$ of matter is a function of the field $\vec{H}$, of the material, and of the magnetic, mechanical and thermodynamical treatments previously applied to the substance.

Figure 1 shows the general form of B versus H in matter. This plot shows that the induction B reaches an asymptotic value B_s called saturation value. There are two distinguishable areas: a *linear zone* (a) and a *saturation zone* (b). In the linear zone ($H < H_s$), we have:

$$\vec{M} = \mu_0 \chi_m \vec{H}$$

where χ_m is the *magnetic susceptibility* of the studied sample.

As a result:

$$\vec{B} = \mu_0 \vec{H}(\chi_m + 1) = \mu_0 \mu_r \vec{H}$$

where $\mu_r = \chi_m + 1$ is the *relative permeability* of the studied substance.

In the saturation zone ($H > H_s$), $\vec{M}$ no longer varies linearly with $\vec{H}$. We can therefore no longer write the equation $\vec{B} = \mu_0 \mu_r \vec{H}$, since μ_r would no longer be a constant, but a function of $\vec{H}$. We can however define a more general local value μ_r^* of the magnetic permeability, by considering variations of B and H:

$$\mathrm{d}|\vec{B}| = \mu_0 \mu_r^* \mathrm{d}|\vec{H}| \qquad \Rightarrow \qquad \mu_r^* = \frac{1}{\mu_o} \frac{\mathrm{d}|\vec{B}|}{\mathrm{d}|\vec{H}|}$$

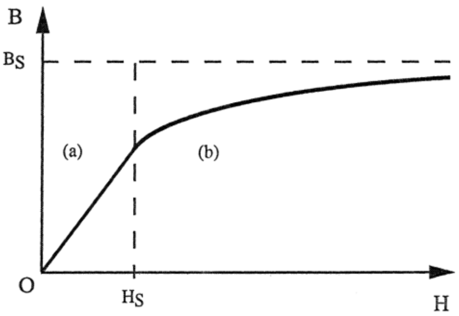

Fig. 1 : Magnetic induction as a function of magnetic field in matter

Depending on the nature of the material, it can have different magnetic properties, that are called *diamagnetism*, *paramagnetism*, or *ferromagnetism*.

2. Diamagnetism

For diamagnetic materials, magnetization $\vec{M}$ varies linearly with $\vec{H}$ and $\chi_m < 0$. Diamagnetism comes from the fact that electron orbits act like small current coils. As a result, all materials present diamagnetic properties, which by the way can be noticed by the presence of permanent magnetic moments. Diamagnetism is temperature independent.

3. Paramagnetism

Certain atoms and ions (oxygen, air, iron salts, etc.) have a magnetic moment of their own. Without a $\vec{H}$ field, these are oriented randomly, and therefore don't show any magnetization on a macroscopic scale. However, applying an external $\vec{H}$ field will results in orienting all magnetic momenta in its direction, and end up with a non zero macroscopic magnetic moment $\vec{M}$. Thermal agitation in the material is enough to disorient the atoms once the $\vec{H}$ field vanishes

If there is no interaction between individual magnetic moments, this effect is called paramagnetism, and is characterized by $\chi_m > 0$. In general, $\vec{M}$ varies linearly with $\vec{H}$. Paramgnetism is temperature dependent.

4. Ferromagnetism

If many magnetic moments orient in the same direction locally, and the coupling between these individual magnetic moments is strong, then thermal agitation is unable to break this alignment under a given temperature (*Curie temperature*). This phenomenon is called ferromagnetism, and *Weiss domains* (areas inside of which all magnetic moments are oriented in the same direction) can then be observed on macroscopic scale. In a ferromagnetic material on which we apply a non zero $\vec{H}$ field, these domains align in the direction of $\vec{H}$ and develop a strong macroscopic magnetization $\vec{M}$.

Ferromagnetism is temperature dependent, and the ferromagnetic state of an object depends on its history ($\vec{H}$ fields previously applied, thermodynamical treatments, etc.). The main ferromagnetic materials are iron, cobalt and nickel.

5. Hysteresis

Hysteresis cycles (Fig. 2) show the connection there exists between the magnetization $\vec{M}$ (or the magnetic $\vec{B}$) field as a function of the applied magnetic induction $\vec{H}$. The cycle characterizes each ferromagnetic body, and its shape depends on the shape of the sample, the mechanical stress applied to it, its temperature, etc.

We can make out:

- The OP curve of *first magnetization*
- The *saturation field* H_s (for which all Weiss domains have the same direction)
- The *remnant induction* B_r
- The *coercive field* H_c
- The overall *symmetry of the cycle* (the points P'(-H_s) et P(H_s) with respect to O)

If we let the H field oscillate between two symmetric limits $-H_m$ et H_m, with respect to O, with $H_s \neq H_m$, we get other cycles that still have O as their centre of symmetry.

A cyclic magnetic field applied to a hysteresis cycle dissipates energy in the ferromagnetic material. The dissipated energy τ over a closed path, with uniform $\vec{H}$ and $\vec{B}$ in a sample of volume V, can be calculated by:

$$\boldsymbol{\tau} = \boldsymbol{V} \oint_{\boldsymbol{C}} \vec{H}\, \delta\vec{B}$$

where C describes the closed path

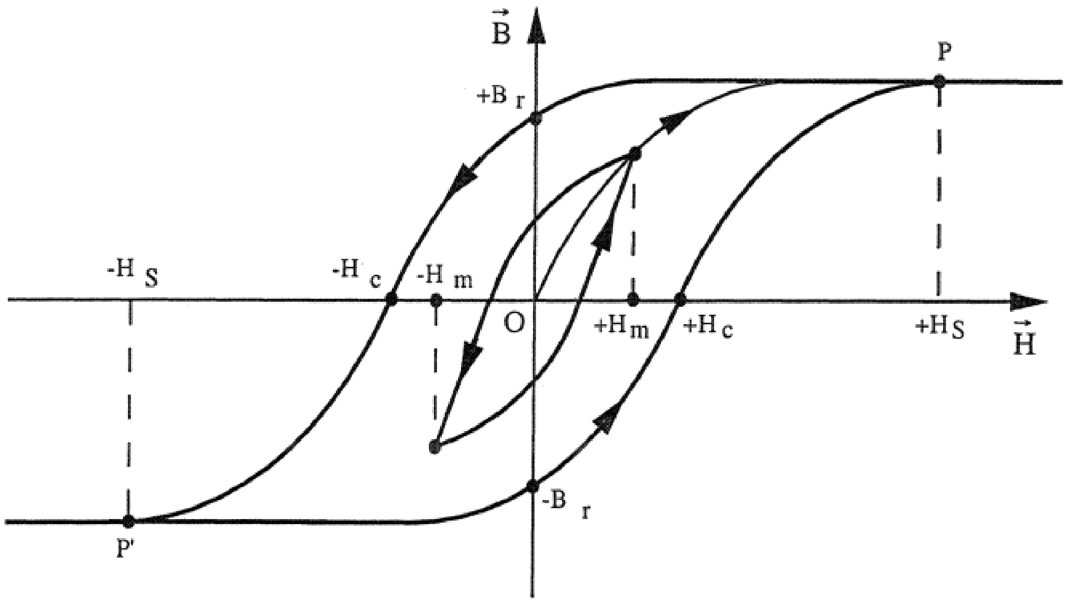

Fig. 2 : Magnetic hysteresis

III. EXPERIMENTAL PROCEDURE

The figures 3 and 4 present the setup that will be used in order to plot the hysteresis cycles of different substances.

We have a *Phywe* transformer, whose primary and secondary coils can be chosen with a certain amount of turns (300, 600, 1200, 2x1800 or 12000 turns), which lets us adjust the sensitivity of the setup, and allows the parallelepipedic samples to be tested on a closed circuit. Also available is a cylindrical transformer with a primary coil with 450 (405) turns, and a secondary coil with 4980 (4920) turns, which allows for rods to be tested as samples, in an open circuit.

The primary coil of the transformer is supplied with an adjustable continuous voltage source, whose polarity can be inverted using an inverter. A 1 Ω resistance is mounted on the circuit. The voltage difference of this resistance is plugged into the x terminal of the x-y plotter.

The secondary coil of the transformer is connected to an integrating setup, i.e. an electronic element whose output voltage is proportional to the integral of the input. The output voltage of the integrator is plugged into the y terminal of the x-y plotter.

The integrator consists of an operational amplifier and an RC circuit, but it isn't necessary to fully understand it here. To start turn on the integrator "On". The circuit then integrates when the switch is on "Integrate". You can reset the integration using the switch in the "Reset" position. When the integrator works, it may happen that a "drift" is observed (on the y axis), in the absence of a variation of H. To obtain hysteresis cycles of good quality, this drift of the integrator must be very accurately compensated using the "drift compensation" potentiometer. To do this, before beginning the recording of a cycle, strongly increase the sensitivity of the axis y, decrease the current and the tension to the minimum and compensate the drift voltage with the potentiometer as precisely as possible. Then, return to the original sensitivity, and start the measurement.

The hysteresis cycle is plotted manually, by consecutive voltage increase and decrease. Do this twice, once for a given polarity, and once by switching it using the inverter (set the current and the voltage to minimum before inverting the polarity). Make sure the sensitivity of the x-y plotter is set high enough in order to get decent results, but not too high that the plotter saturates.

Also note that the integrator is an electronic circuit, and its output voltage is therefore also limited by two saturation values. To adjust the magnitude of the integrator's output voltage, try changing the coils of the primary and/or secondary coils. Again, look for high voltages, but avoid saturation.

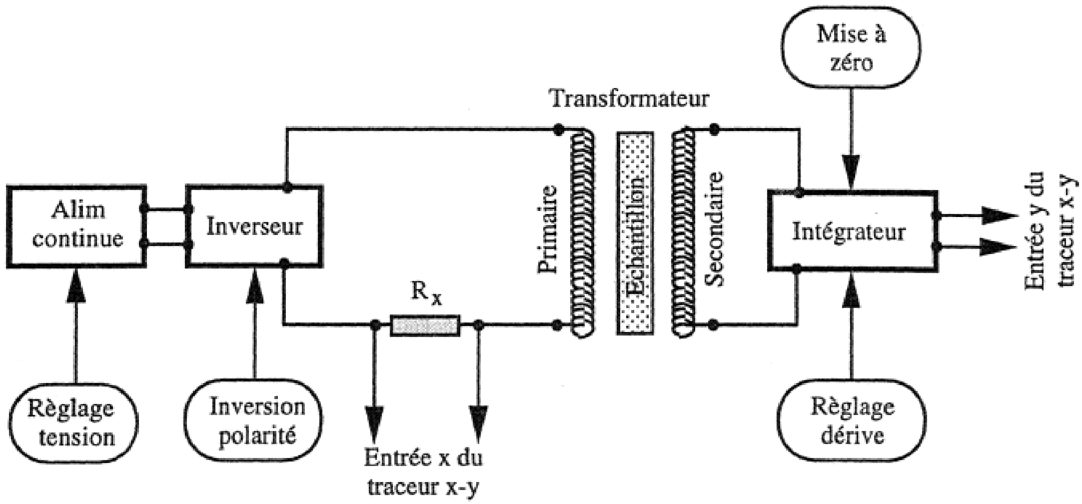

Fig. 3 : Scheme of the experimental setup.

IV. SUGGESTED EXPERIMENTS

- Explain why the plotter's x-axis voltage is proportional to the applied H-field. Can we calibrate the x-axis of the plotter (for instance in [A/m] per V)?
- Explain why the y-axis voltage is proportional to the B-field in the material. Can we calibrate the y-axis of the plotter (for instance in [Vs/m^2] per V)? Try to reason independently for each setup (*Phywe* and cylindrical transformer).

Choose one of the two setups for the following of the experiment (*Phywe* or cylindrical transformer)

If *Phywe* chosen:
- Plot a hysteresis cycle using the *Phywe* transformer, first as an open circuit, then as a closed one. Verify that we can obtain different cycles (several values of H_m). Determine what the essential parameters are. What happens for an asymmetrical sweep (e.g. $H_m - 2H_m$)?
- Same as the previous point, but using different materials (steel, aluminum, copper, etc.). Classify the samples from their magnetic properties.
- Determine the relative permittivity μ^* for each materials.
- Try to superpose multiple samples of the same material and observe the changes in the hysteresis. What can you conclude about?
- Observe the change in the hysteresis loop with the *Phywe* block as a function of the separation with the transformer. For this purpose, you have at your disposal multiple bars of 0.5 mm tick that you can insert between the block and the transformer. Try to find some explanation.
- The *Phywe* block is made of multiple thin plates. Measure the hysteresis loop for plates oriented vertically and horizontally. Conclude about.

If cylindrical transformer:
- Measure the hysteresis loop for the vacuum (no sample). Primary is the part with the less number of turns.
- Same measurements, using the different available materials (steel, aluminium, copper, brass, nickel, etc.).
- Find a procedure in order to calibrate the axis of the x-y plotter.
- Determine (numerically for some samples) the various values related with the hysteresis loop ($H_s, B_s, B_r, \ldots$), and the permittivity of each samples.
- List several different applications for magnetic materials, pointing out the particular characteristic of the hysteresis cycle used for the applications.

Other ideas:

- What could be technological applications for magnetic materials and with characteristic of the hysteresis loop would be used?
- Measure the *hard ferromagnetic material*. Just replace the used transformer with the one which resembles to a ring. You will find it in the very last tray. What characteristics are attributed to *hard materials*?
- Any other personal ideas.

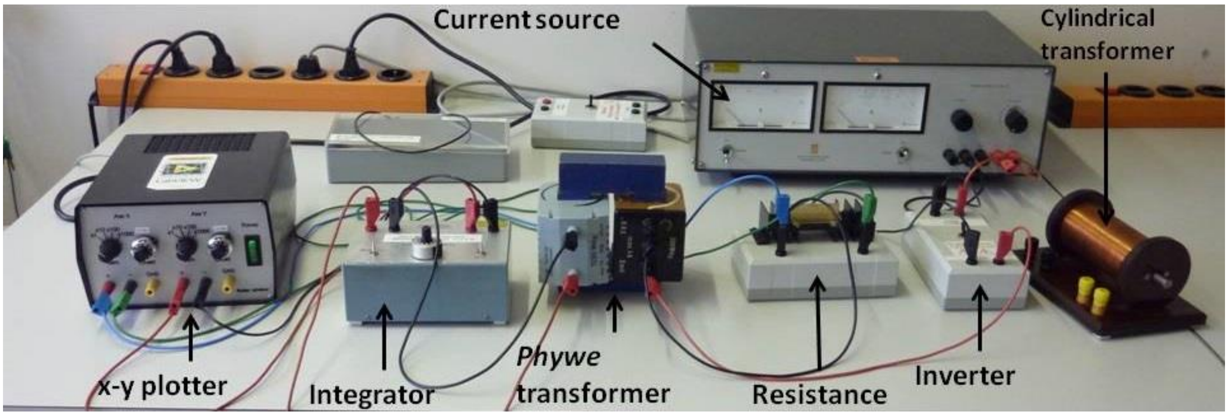

Fig. 4 : Image of the setup