Outline

• Ferromagnetism
• Measurement of the magnetic properties of the materials
• Lab experimental setup and experiments
• Some results
Ferromagnetism. Definition.

Some materials below a certain temperature ($T_c$) give rise to the magnetic field in absence of an applied field.

This magnetization is called spontaneous, the phenomenon – ferromagnetism and materials exhibiting this feature – ferromagnetics.

The main parameter of the ferromagnetic phase transition is spontaneous magnetization

Typical behavior of spontaneous magnetization as function of temperature
Ferromagnetic materials.

Aleksandr Stoletov (1839 – 1896)

“Stoletov” curve

\[ \chi = \frac{dM}{dH} \]

Stoletov performed pioneer works in area of ferromagnetic materials but better known by his research in photoelectric effect.

<table>
<thead>
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<th>Material</th>
<th>Curie temp. (K)</th>
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<tbody>
<tr>
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</tr>
<tr>
<td>Fe₂O₃⁺</td>
<td>948</td>
</tr>
<tr>
<td>FeOFe₂O₃⁺</td>
<td>858</td>
</tr>
<tr>
<td>NiOFe₂O₃⁺</td>
<td>858</td>
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<tr>
<td>MgOFe₂O₃⁺</td>
<td>713</td>
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<tr>
<td>MnBi</td>
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<tr>
<td>Ni</td>
<td>627</td>
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<td>CrO₂</td>
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<tr>
<td>MnAs</td>
<td>318</td>
</tr>
<tr>
<td>Gd</td>
<td>292</td>
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</table>
Domains. Hysteresis loop.

* Courtesy Wikipedia
Kerr Effect. Visualization of the Domains

John Kerr
17 Dec 1824 – 15 Aug 1907

The Diagram of Typical Kerr Microscope

Courtesy of Radboud University, Nijmegen
The Netherlands
Several grains of NdFeB with magnetic domains made visible via contrast with a Kerr microscope.

Courtesy of Wikipedia

Kerr microscope
Courtesy of University of Uppsala (Sweden)
Moving domain walls in a grain of silicon steel caused by an increasing external magnetic field

Courtesy of Wikipedia
Hysteresis Loops.
Remagnetization loses

\[ W = V \int HdB \]

By cycling around the loop

\[ W_{\text{loop}} = V \oint HdB = V \times \text{Loop area} \]

Energy of the magnetic field
“Hard” materials. Application.

Hard drives, floppy, magnetic tape

RAM memory

Permanent magnets

Chokes, inductors

Power transformers
Magnetic Field, Susceptibility etc.

\[ B = \mu_0 \left( H + M \right) \]

- \( B \) – magnetic induction
- \( M \) – magnetization, in general \( M(H) \)

\[ M = \chi H \]

- \( \chi \) – magnetic susceptibility, in general \( \chi(H) \)

\[ B = \mu_0 \left( 1 + \chi \right) H = \mu_0 \mu_r H = \mu H \]

- \( \mu_r = 1 + \chi \)

\[ \mu = \mu_0 \mu_r = \frac{dB}{dH} ; \quad \mu_r = \frac{1}{\mu_0} \frac{dB}{dH} \]
Modulation Spectroscopy

\[ B = f(H) \quad H = H_0 + H_1 \sin \omega t \]

\[ B = f(H_0) + \frac{df}{dH} (H_1 \sin \omega t) + ... \]

\[ H_1 = \text{const} \]

\[ B_\omega \sim \frac{dB}{dH} \]
Measuring the magnetic permeability

By applying a small modulation of the H field we can measure the derivative of the B-H hysteresis loop or dependence of the magnetic permeability on H field.

\[ \mu(H_0, \omega) = \mu_0 (1 + \chi(H_0, \omega)) = \left. \frac{dB}{dH} \right|_{H_0,\omega} \]
Setup #1. Investigation of the hysteresis loops.
Setup #1. Investigation of the hysteresis loops.

\[ H = \frac{N_p I_p}{2\pi r} \]

\[ H = H_0 + H_1 \cos \omega t \]
Major/minor loops.
Demagnetization

Waveform of H-field
Demagnetization of 4C65 toroid from Ferroxcube
Fig. A family of AC hysteresis loops for grain-oriented electrical steel (\(B_R\) denotes remanence and \(H_C\) is the coercivity). Courtesy Zureks (Wikipedia)
Measuring the magnetic permeability

DC current profile and magnetic permeability of Magnetics ZW44715TC

\[ \mu_r \approx 12700 \]
From permeability to B-H hysteresis loop

Step#1. Performing one fast IDC scan the based on the result preparing the “smart” IDC profile

Step#2. Performing precise scan the. Plotting raw data based

Voltage units measured by SR830

Current in primary coil in A
Step #3. What we are measuring? Calibration.

Lock-in measures emf on the pickup coil

\[ V_{\text{lock-in}} = -\frac{d\Phi}{dt}; \Phi = \vec{B} \cdot \vec{S} \]

Here \( I_p \) is ac current in primary coil L3; \( I_p = \frac{V_0 \sin(\omega t)}{R_2} \)
Step#3. What we are measuring?
Calibration.

Primary coil of \( N_p \) turns supplied by current \( I_p \) creates magnetic field \( H \) and flux \( d\Phi \)

For toroid: \( H = \frac{N_p I_p}{2\pi r} \)

\[ d\Phi = \mu \int \vec{H} \cdot d\vec{a} = \frac{\mu I N t}{2\pi} \int_{R_1}^{R_2} \frac{dr}{r} = \frac{\mu I N t}{2\pi} \ln \frac{R_2}{R_1} \]

\( da = dr \cdot t \)
Step#3. What we are measuring? Calibration.

**Total flux detected by pickup coil:**

\[
\Phi = N_{\text{pickup}} d\Phi = \frac{\mu N_{\text{pickup}} N_p I_p t}{2\pi} \ln \frac{R_2}{R_1}
\]

**Np and Ip number of turns of AC primary coil and AC rms current**

**Inductance of the toroid:**

\[
L = \frac{\Phi}{I} ; \quad L = \mu_r L_0 = (\mu' - i \mu'') L_0
\]

\[
L_0 = \frac{\mu_0 N_{\text{pickup}} N_p t}{2\pi} \ln \frac{R_2}{R_1}
\]
From permeability to B-H hysteresis loop

\[ V_{\text{lock-in}} = \mu_r L_0 \frac{dI_p}{dt} \]

\[ \frac{dI_p}{dt} = \frac{V_0}{R_2} \omega \cos(\omega t) \]

\[ H_0 = \frac{N_p I_{\text{DC}}}{2\pi r} \]
From permeability to B-H hysteresis loop

Step#4. From $\mu_r(H)$ to B-H

$$\mu(H_0) = \mu_0 \mu_r(H_0) = \frac{dB}{dH} \bigg|_{H_0}$$

After integrating

$$B(H) = \mu_0 \int \mu_r(H) dH$$
Software issue

Icon on the desktop

Magnetic Lab v9.2

Preparation of the profile of the experiment

B-H measurement

Demagnetization

Experiment

B-H curve

Main menu

Experiment

Temperature scan

1st week experiment

2nd week experiment

Preparation

Measurement

Demagnetization

EXIT Program

4/8/2019

illinois.edu
Software issue
Measuring profile preparation. Using profile template

Open a new file
Create a new file
Save prepared file for future use
Software issue

Software issue

Measuring profile preparation

Example of simple protocol

Advanced profile
Software issue

Measurement Window

Lock-in amplifier response

The profile of the applied DC current

Structure of the data file (B-H experiment)

<table>
<thead>
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<th>Long</th>
<th>time (s) =</th>
<th>f (Hz)</th>
<th>Uac (Vrms)</th>
<th>Idc (A)</th>
<th>X (V)</th>
<th>Y (V)</th>
<th>R (V)</th>
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Data analysis using Origin

To calculate the permeability better to use the template:

```
\" enr-file-03\phyinst\APL Courses\PHYCS401\Common\Origin templates\AC magnetic Lab\MU_CALCULATION.otw
```

It does not contain the equations – you have to write them

<table>
<thead>
<tr>
<th>time (s)</th>
<th>f (Hz)</th>
<th>UacVrms (V)</th>
<th>Idc (A)</th>
<th>X (V)</th>
<th>Y (V)</th>
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</table>

Parameters:
- Npick up
- Nac primary
- h(m)
- r2
- r1
- Ndc primary
Data analysis using Origin. Integrating.

\[ B(H) = \mu_0 \int \mu_r(H) dH \]
Data analysis using Origin. Integrating.

\[ B(H) = \mu_0 \int \mu_r(H) dH + \text{offset} \]
References

- Information about magnetic materials can be found in:
  \engr-file-03\phyinst\APL
courses\PHYCS401\Experiments\AC_Magnetization\Magnetic Materials

- **SR830 manual:**  \engr-file-03\phyinst\APL
courses\PHYCS401\Common\EquipmentManuals\SR830m.pdf