AC Measurement of Magnetic Susceptibility

Physics 401, Fall 2018
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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 \textit{spontaneous}, the phenomenon – ferromagnetism and materials exhibiting this feature – \textit{ferromagnetics}.

The main parameter of the ferromagnetic phase transition is \textit{spontaneous} magnetization.

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

Aleksandr Stoletov (1839–1896) performed pioneer works in the area of ferromagnetic materials but better known by his research in photoelectric effect.

### “Stoletov” curve

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

### Curie temperatures (K)

<table>
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<th>Material</th>
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<tr>
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<td>948</td>
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<tr>
<td>FeOFe(_2)O(_3)*</td>
<td>858</td>
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<tr>
<td>NiOFe(_2)O(_3)*</td>
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<td>MgOFe(_2)O(_3)*</td>
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<td>627</td>
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<td>MnSb</td>
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<tr>
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<td>CrO(_2)</td>
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<td>MnAs</td>
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<tr>
<td>Gd</td>
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</table>
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
Domains

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)
Domains

Moving domain walls in a grain of silicon steel caused by an increasing external magnetic field

Courtesy of Wikipedia
Hysteresis Loops.
Remagnetization loses

\[ W = V \int H dB \]

By cycling around the loop

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

Energy of the magnetic field

“Soft” Ferromagnetic Material

“Hard” Ferromagnetic Material
“Hard” materials. Application.

- RAM memory
- Permanent magnets
- Hard drives, floppy, magnetic tape

Chokes, inductors

Power transformers
Magnetic Field, Susceptibility etc.

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

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

\[ M = \chi H \]

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

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

\( \mu_r = 1 + \chi \)

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

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

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

\[ H_1 = \text{const} \]

\[ B_\omega \sim \frac{dB}{dH} \]
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
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
From permeability to B-H hysteresis loop

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; \( I_p = \frac{V_0 \sin(\omega t)}{R_2} \)
From permeability to B-H hysteresis loop

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: $H = \frac{N_p I_p}{2\pi r}$

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

$da = dr \cdot t$
From permeability to B-H hysteresis loop

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

1st week experiment

2nd week experiment

Preparation of the profile of the experiment

B-H measurement

Demagnetization

Experimnt

B-H curve

Preparation

Measurement

Demagnetization

Main menu

Experiment

Temperature scan

EXIT Program

Icon on the desktop

Magnetic Lab v9.2

11/12/2018
Software issue

Measuring profile preparation. Using profile template
Software issue


B-H PROFILE

The shown profile is a saved one from the previous experiment.

You can use it, load saved profile or create a new one.

Open a new file
Create a new file
Save file
Exit
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)

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<tr>
<th></th>
<th>time (s)</th>
<th>f (Hz)</th>
<th>Uac (Vrms)</th>
<th>Idc (A)</th>
<th>XV (V)</th>
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Data analysis using Origin

To calculate the permeability better to use the template:

```
\engr-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

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Raw data

Calculated results
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\`