AC Measurement of Magnetic Susceptibility

Physics 401, Spring 2016
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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 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

![Graph showing the typical behavior of spontaneous magnetization as function of temperature.](image)
Ferromagnetic materials.

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

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

### Materials and Curie Temperatures (K)

<table>
<thead>
<tr>
<th>Material</th>
<th>Curie temp. (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co</td>
<td>1388</td>
</tr>
<tr>
<td>Fe</td>
<td>1043</td>
</tr>
<tr>
<td>FeO (_2)</td>
<td>948</td>
</tr>
<tr>
<td>FeOFeO (_2) (_3)</td>
<td>858</td>
</tr>
<tr>
<td>NiOFeO (_2) (_3)</td>
<td>858</td>
</tr>
<tr>
<td>MgOFeO (_2) (_3)</td>
<td>713</td>
</tr>
<tr>
<td>MnBi</td>
<td>630</td>
</tr>
<tr>
<td>Ni</td>
<td>627</td>
</tr>
<tr>
<td>MnSb</td>
<td>587</td>
</tr>
<tr>
<td>MnOFeO (_2) (_3)</td>
<td>573</td>
</tr>
<tr>
<td>Y (<em>3)FeO (</em>{12}) (_3)</td>
<td>560</td>
</tr>
<tr>
<td>CrO(_2)</td>
<td>386</td>
</tr>
<tr>
<td>MnAs</td>
<td>318</td>
</tr>
<tr>
<td>Gd</td>
<td>292</td>
</tr>
</tbody>
</table>
Domains. Hysteresis loop.

* Courtesy Wikipedia
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

\[ W = V \int H dB \]

Energy of the magnetic field

By cycling around the loop

\[ W_{\text{loop}} = V \oint H dB = V \times \text{Loop area} \]
“Hard” materials. Application.

- RAM memory
- Permanent magnets

Hard drives, floppy, magnetic tape

Power transformers

Chokes, inductors
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 \( \chi(H) \)

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

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

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

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

\[ H_1 = \text{const} \]

\[ B_\omega \sim \frac{dB}{dH} \]
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

B saturation

H

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Demagnetization of 4C65 toroid from Ferroxcube
Hysteresis Loops

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

$\mu_{max} \approx 12700$
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
From permeability to B-H hysteresis loop

Step#3. What we are measuring?
Calibration.

Lock-in measures emf on the pickup coil

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

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

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

$R_2 < r < R_1$

da=dr*t

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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

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

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

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

\[ I_p = \frac{V_0}{R_I} \sin \omega t \]

\[ V_0 \text{ – amplitude of the sine wave from Wavetek FG} \]

\[ V_{\text{lock-in}} \sim \omega \]
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

Preparation

Measurement

Demagnetization

1st week experiment

2nd week experiment

Main menu

Experiment

Temperature scan

EXIT Program

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Software issue
Measuring profile preparation. Using profile template

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

<table>
<thead>
<tr>
<th>Step(A)</th>
<th>Istart(A)</th>
<th>Istop(A)</th>
<th>Step(A)</th>
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<tbody>
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<td>1:1</td>
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<td>6:1</td>
<td>0</td>
<td>2m</td>
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</tr>
</tbody>
</table>
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)
To calculate the permeability better to use the template:

```
\aplcourses\phyinst\common\origin templates\AC magnetic Lab\MU_CALCULATION.otw
```

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

<table>
<thead>
<tr>
<th>N</th>
<th>time (s)</th>
<th>f (Hz)</th>
<th>Uac(Vrms)</th>
<th>Ioc(A)</th>
<th>X(Y)</th>
<th>Y(Y)</th>
<th>R(Y)</th>
<th>A(L)</th>
<th>E(Y)</th>
<th>L0(Y)</th>
<th>mu1(Y)</th>
<th>mu2(Y)</th>
<th>H(Y)</th>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Parameters:
- \( N_{pickup} \)
- \( N_{ac\ primary} \)
- \( h(m) \)
- \( r_2 \)
- \( r_1 \)
- \( N_{dc\ primary} \)

Raw data

Parameters

Calculated results

4/11/2016
Data analysis using Origin. Integrating.

\[ B(H) = \mu_0 \int \mu_r(H) dH \]
$B(H) = \mu_0 \int \mu_r(H) dH + offset$
References

- Information about magnetic materials can be found in:
  \`\`\`\texttt{\textbackslash \textbackslash engr-file-03\textbackslash phyinst\textbackslash APL Courses\textbackslash PHYCS401\textbackslash Experiments\textbackslash AC\_Magnetization\textbackslash Magnetic Materials}\`\`\`

- **SR830 manual:** \`\`\`\texttt{\textbackslash \textbackslash engr-file-03\textbackslash phyinst\textbackslash APL Courses\textbackslash PHYCS401\textbackslash Common\textbackslash EquipmentManuals\textbackslash SR830m.pdf}\`\`\`