Fields and Waves

Lesson 3.6

MAGNETIC MATERIALS
Today’s Lesson:

- linkage between $H$ and $B$ fields
- $M$ - magnetization
- re-visit Ampere’s Law
- boundary conditions
- permanent magnets
Magnetic properties tend to either very strong or very weak. Vast majority of materials:
- Ferromagnets (Fe) and permanent magnets
- Exhibit strong non-linear effects
- Demonstrate “memory” or hysteresis effects

Recall in electrostatics that most materials have moderate effect:
$$1 < \varepsilon < 10$$
In Quantum mechanics, atoms have “spin”

In the classical picture:
• electron orbits the nucleus
• acts like a current loop

Usually in most materials, the loops have random orientation - so the net effect is small

In ferromagnets, neighboring atoms have spins that are aligned - strong effects
The individual current loops can be thought of as having a dipole moment, $\vec{m}$. 

Fig. 10.7 Some magnetic field lines in the field of a magnetic dipole, that is, a small loop of current.
Magnetic and Electric Dipole Moment

The current loop approximates the dipole moment, $\vec{m}$.

E-field of electric dipole

B-field of magnetic dipole

Far-fields look the same for both types of dipoles.
In general, one can write:

\[ \vec{M} = \sum_i \vec{m}_i \]

magnetization

\[ \vec{H} = \frac{\vec{B}}{\mu_0} - \vec{M} \]

where,

- flux due to all sources
- flux due to atomic sources
- flux due to free current (e.g. conduction current, e-beam)
Relationship between $\vec{B}$ & $\vec{H}$

Maxwell’s equation:
\[ \oint \vec{H} \cdot d\vec{l} = I_{\text{net}} = \int \vec{j} \cdot d\vec{s} \]
these are free-currents

- we can determine $\vec{H}$ without determining $\vec{M}$

In most general form:
\[ \vec{B} = \mu_0 \cdot (\vec{H} + \vec{M}) \]

If, $\vec{M} \propto \vec{H}$
\[ \Rightarrow \vec{B} = \mu \cdot \vec{H} = \mu_r \cdot \mu_0 \cdot \vec{H} \]

Values,
\[ \mu_0 = 4\pi \times 10^{-7} \text{ } H / m \]
\[ \mu_r = 1 \times 10^{-4} \text{ for most materials} \]
\[ \Rightarrow \approx 5000 \text{ for iron} \]
Curves for $\vec{B}$ & $\vec{H}$

Typical B-H Curve for materials

For course, use ideal curve:

$\vec{M} \propto \vec{H}$
Boundary Conditions

Do problem 1a: use \( \oint \vec{H} \cdot d\vec{l} = I_{\text{net}} \) then apply \( \vec{B} = \mu \cdot \vec{H} \)

Boundary Conditions:

Normal component:

\( \oint \vec{B} \cdot d\vec{s} = 0 = \int_{\text{TOP}} \vec{B} \cdot d\vec{s} + \int_{\text{BOTTOM}} \vec{B} \cdot d\vec{s} \)

\( B_{n1} \cdot \text{AREA} - B_{n2} \cdot \text{AREA} = 0 \)

\( \therefore B_{n1} = B_{n2} \)

Take \( h \ll a \) (a thin disc)

- ignore contribution from the sides
Boundary Conditions

Tangential component:

\[
\oint \vec{H} \cdot d\vec{l} = H_{t2} \cdot w - H_{t1} \cdot w = I_{net}
\]

\( I_{net} \) can only be due to surface currents \( = J_s \cdot w \)

\[
\vec{H}_{t2} - \vec{H}_{t1} = \vec{J}_s
\]

or

\[
\hat{a}_n \times (\vec{H}_2 - \vec{H}_1) = \vec{J}_s
\]

If non-conductor, \( J_s = 0 \), then, \( H_{t1} = H_{t2} \)

If conductor in 1 and \( H_{t1} \to 0 \), then, \( H_{t2} = J_s \)
Magnetic Materials

Do Problems 1b and 2

Problem 2: Field lines exit normally in high $\mu$ materials

Also, field lines like to travel through high $\mu$ materials

Transformers:

- use IRON to direct flux
  - primary and secondary windings intercept almost all the flux - no need for “smoothly-wound” coils
  - Noise reduction
  - increase Inductance with increasing $\mu$

Do Problem 3