10-BH Curve

ECEGR 450
Electromechanical Energy Conversion

Overview

- Introduction
- Properties of Magnetic Materials
- BH-Curve
- Magnetic Losses

Questions

Why are magnets magnetic?

Introduction

- Analysis of transformers and rotating machines (generators/motors) requires understanding how the magnetic flux behaves in magnetic circuits
- Graphical relationship between Flux and Magnetic Field Intensity is known as the BH curve

See ebook: Michael Coey, *Magnetism and Magnetic Materials*, Cambridge University Press, 2010. [available online Seattle U library]

Magnetic Materials

- Properties of materials influences the design of machines
- Recall that flux density is a function of permeability, magnetic field intensity and magnetization
  $\mathbf{B} = \mu_0(\mathbf{H}+\mathbf{M})$
- We will next examine properties of magnetic materials

Magnetic Materials

Three general types of magnetic materials
- Diamagnetic
- Paramagnetic
- Ferromagnetic

Diamagnetic Materials

- Materials that create a magnetic field that opposes an applied magnetic field
- A repulsive force (usually weak) is experienced
  - Superconductors exhibit a strong force
  - Can be used to make things levitate
  - Negative susceptibility

Material	Relative Permeability
Bismuth	0.999981
Copper	0.999991
Silver	0.999980
Water	0.999991

Paramagnetic Materials

- Materials that create a magnetic field in the direction of an applied magnetic field
- A attractive force (usually weak) is experienced
  - Positive susceptibility

Material	Relative Permeability
Air	1.000304
Aluminum	1.000023
Oxygen	1.001330
Platinum	1.000014

Ferromagnetic Materials

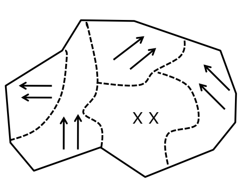
- Experience a strong attractive force to an applied magnetic field
  - Force can be several thousand times stronger than that in paramagnetic materials
  - Resulting magnetic field may be stronger than the applied field
- Ferromagnetic materials include
  - Iron, cobalt, nickel
- Ferromagnetic materials are commonly used in machines so we will discuss them in more detail

Magnetic Dipoles

- An electron orbiting a nucleus is a ring of current
- We know that current has an associated magnetic field
  - Orbital magnetic moment
- Electrons also rotate around their own axis
  - Spin magnetic moment
- Net magnetic moment constitutes a magnetic dipole

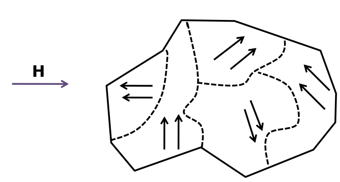
Ferromagnetic Materials

- In some materials the magnetic dipoles in a region may be aligned (magnetic domains)
- Domains are usually randomly oriented and there is no net magnetic field



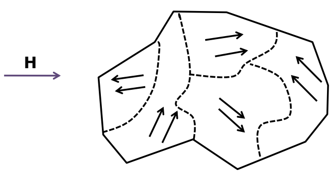
Ferromagnetic Materials

- Assume we apply a magnetic field **H** to the material
- A magnetic flux density is created inside the material according to: $\mathbf{B} = \mu_0(\mathbf{H}+\mathbf{M})$



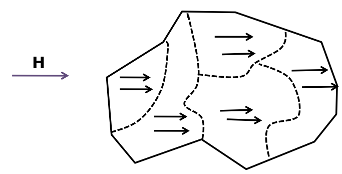
Ferromagnetic Materials

- As **H** increases, some of the dipoles begin to align with **H**
- Flux density begins to increase at a faster rate than the applied magnetic field

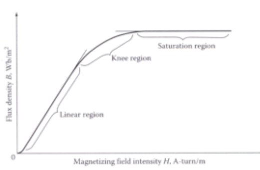


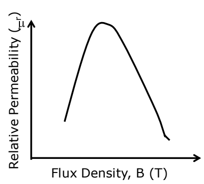
Ferromagnetic Materials

- For some value of **H** all of the magnetic domains are in the direction of **H**
- Further increases in **H** still increases **B**, but at a much slower rate (permeability of free space)



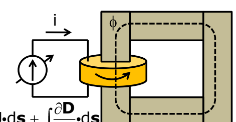
B-H Curve





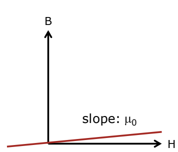
B-H Curve

- Assume material is not magnetized and i = 0
  - **M** = 0
  - **H** = 0 } **B** = 0
- What happens to **H** and **B** as i increases?
  - H increases (+) $\oint_c \mathbf{H}\cdot d\ell = \oint_s \mathbf{J}\cdot d\mathbf{s} + \int_s \frac{\partial \mathbf{D}}{\partial t}\cdot d\mathbf{s}$
  - B increases (+) $\mathbf{B} = \mu_0(\mathbf{H}+\mathbf{M})$



B-H Curve

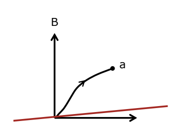
If material is not magnetic, then **M** = 0 and **B** and **H** are linearly related by μ_0



B-H Curve

- If materials are magnetic, then **M** increases along with **H** (the material becomes magnetized)
- **B** increases at a rate faster than μ_0:

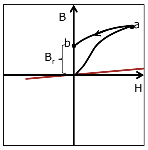
$\mathbf{B} = \mu_0(\mathbf{H}+\mathbf{M})$



B-H Curve

Now i is decreased from positive to zero to negative

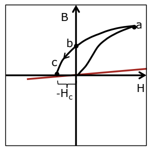
H decreases to zero
M slowly decreases, but remains positive
B does not decrease to zero
Point b: B_r = Residual Flux Density



Many magnetic domains are aligned in the +**H** direction.
Material is still magnetized.

$\mathbf{B} = \mu_0(\mathbf{H}+\mathbf{M})$

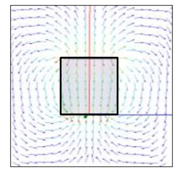
H is now negative
M is positive, and **H** + **M** = 0 at point c
B is equal to 0 at point c
Point c: $-H_c$ = Coercive force



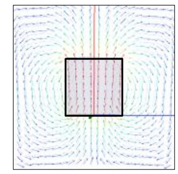
Note: second quadrant. **B** and **H** are in opposite directions. Important for permanent magnets.

Magnetic Fields Internal to a Magnet

Magnetic Field Intensity **H**



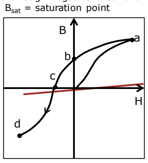
Magnetic Flux Density **B**



From point b to c (**H** and **B** are in opposite directions)

B-H Curve

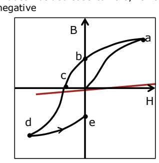
i continues to become more negative
H becomes more negative
M becomes negative
B passes through negative linear and knee regions
Point d: B_{sat} = saturation point



Note: third quadrant. **B** and **H** are in the same direction.
Material magnetized in opposite direction.

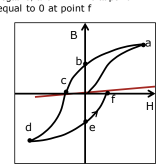
$\mathbf{B} = \mu_0(\mathbf{H}+\mathbf{M})$

i increases to 0
H increases to 0
M is negative, but magnitude decreases
B does not decrease to zero, remains negative



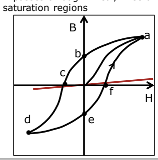
B-H Curve

i is now positive and increases
H becomes positive
M is negative, and **H** + **M** = 0 at point f
B is equal to 0 at point f



$\mathbf{B} = \mu_0(\mathbf{H}+\mathbf{M})$

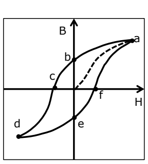
i increases
H is positive and increases
M becomes positive
B passes through linear, knee and saturation regions



If current decreases operating point b will be obtained (nearly)

B-H Curve

- BH curve also known as hysteresis loop
- BH curve dependent on material and its shape
- Area inside hysteresis loop is the hysteresis loss
  - Energy required to overcome friction in changing domain orientation

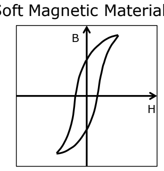


Side Note: Generally $H = H' + H_d$ where
H: internal field
H_d is the demagnetizing field
H': external (applied field)
Since a closed magnetic circuit is used, H_d = 0 and H = H', so the BH curve is also BH' curve.

B-H Curve

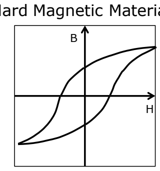
What are the applications of soft and hard magnetic materials?

Soft Magnetic Materials



Easily magnetized, demagnetized
Low coercivity
High permeability
Low core loss

Hard Magnetic Materials



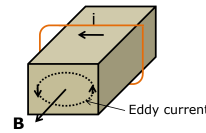
Difficult to magnetize, demagnetize
High coercivity
High maximum energy product
High core loss

Magnetic Losses

- Losses in a machines include magnetic loss
- Two types:
  - Eddy-Current loss
  - Hysteresis loss

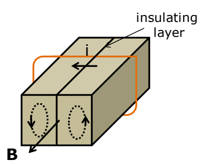
Eddy Current Losses

- Time varying flux in a magnetic circuit induces a voltage in a coil, but also in the material that comprises the magnetic circuit
- The current induced in the material is known as eddy currents, and reduces the efficiency of the machine
  - Eddy current cause heating
  - Flux caused by eddy current opposes applied magnetic field, acting to demagnetize the core



Eddy Current Losses

- Eddy currents can be reduced by introducing a thin insulating material in the direction of the current
- These laminations are common in machines



Summary

- Ferromagnetic materials have a non-linear BH curve
- Magnetic flux increases due to alignment of magnetic domains
- Three distinct regions: linear, knee and saturation
  - Permeability is low in saturated region, generally avoid operation here
- Energy loss associated with shape of BH curve