

PHYS11 CH: 22-23

Magnetism and Electromagnetic Induction

Mr. Gullo

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Outline

- 1 Introduction to Magnetism
- 2 Magnetic Forces
- 3 Magnetic Fields from Currents
- 4 Electromagnetic Induction
- 5 Applications
- 6 Inductance and AC Circuits
- 7 Example Problems
- 8 Summary

Learning Objectives

By the end of this presentation, you will be able to:

- Describe the properties of magnets and magnetic fields
- Apply the right hand rules to determine directions of magnetic forces and fields
- Calculate magnetic forces on moving charges and current-carrying conductors
- Explain electromagnetic induction and apply Faraday's law
- Understand the operation of generators, motors, and transformers
- Calculate inductance and analyze RL and RLC circuits

Magnets and Magnetic Fields

- Magnets have north and south poles
- North pole: attracted to Earth's geographic north
- Like poles repel, unlike poles attract
- Poles always occur in pairs (no magnetic monopoles)
- All magnetism is created by electric current

[Image of bar magnets showing attraction between opposite poles and repulsion between like poles]

Magnetic Field Lines

Properties of Magnetic Field Lines

- ① Field is tangent to the magnetic field line
- ② Field strength is proportional to line density
- ③ Field lines cannot cross
- ④ Field lines are continuous loops

[Diagram showing magnetic field lines around a bar magnet]

Ferromagnets and Electromagnets

Ferromagnetic Materials:

- Iron, cobalt, nickel, gadolinium
- Atoms act like small magnets
- Form domains where magnetic moments align
- Curie temperature: above this temperature, ferromagnetism disappears

[Image showing magnetic domains in a ferromagnetic material]

Electromagnets:

- Current through a wire creates magnetic field
- Adding ferromagnetic core increases field strength
- Applications: motors, generators, MRI machines

Force on a Moving Charge

Magnetic Force Formula

$$\vec{F} = q\vec{v} \times \vec{B} \quad \text{or} \quad F = qvB \sin \theta \quad (1)$$

- q = charge (C)
- v = velocity (m/s)
- B = magnetic field strength (T)
- θ = angle between \vec{v} and \vec{B}
- Direction determined by Right Hand Rule 1 (RHR-1)

[Illustration of Right Hand Rule 1]

Right Hand Rule 1 (RHR-1)

RHR-1 for Force on a Moving Charge

Point the thumb of your right hand in the direction of the velocity \vec{v} , fingers in the direction of the magnetic field \vec{B} , and the force \vec{F} is perpendicular to the palm.

- For negative charges, force is in opposite direction
- Force is always perpendicular to both \vec{v} and \vec{B}
- When \vec{v} and \vec{B} are parallel, $\vec{F} = 0$

Motion of Charged Particles in Magnetic Fields

- When velocity perpendicular to field, particles move in circular path
- Radius of circular path: $r = \frac{mv}{qB}$
- Magnetic force provides centripetal force
- Period of revolution independent of speed
- Helical path when velocity has component parallel to field

[Diagram showing circular motion of charged particle in magnetic field]

Force on Current-Carrying Conductors

Magnetic Force on a Current-Carrying Conductor

$$\vec{F} = I\vec{l} \times \vec{B} \quad \text{or} \quad F = IlB \sin \theta \quad (2)$$

- I = current (A)
- l = length of conductor (m)
- B = magnetic field strength (T)
- θ = angle between \vec{l} and \vec{B}
- Direction follows RHR-1 with thumb in direction of current

[Diagram showing force on a current-carrying wire in a magnetic field]

Torque on Current Loops

Torque on a Current Loop

$$\tau = NIAB \sin \theta \quad (3)$$

- N = number of turns
- I = current (A)
- A = area of loop (m^2)
- B = magnetic field strength (T)
- θ = angle between loop normal and \vec{B}

Applications: Electric motors, meters [Diagram of a current loop in a magnetic field showing torque]

Magnetic Fields Produced by Currents

Magnetic Field from a Long Straight Wire

$$B = \frac{\mu_0 I}{2\pi r} \quad (4)$$

- $\mu_0 = 4\pi \times 10^{-7} \text{ T}\cdot\text{m/A}$ (permeability of free space)
- I = current (A)
- r = distance from wire (m)
- Direction determined by Right Hand Rule 2 (RHR-2)

[Diagram showing magnetic field lines around a current-carrying wire]

Right Hand Rule 2 (RHR-2)

RHR-2 for Magnetic Field from Current

Point the thumb of your right hand in the direction of the current, and your fingers curl in the direction of the magnetic field lines.

- Field lines form concentric circles around a straight wire
- Field strength decreases with distance from wire
- Total field from any current path is the vector sum of fields from all segments

Magnetic Fields from Loops and Solenoids

Circular Loop:

$$B = \frac{\mu_0 I}{2R} \quad (\text{at center}) \quad (5)$$

- R = radius of loop (m)
- Direction from RHR-2

Solenoid:

$$B = \mu_0 n I \quad (\text{inside}) \quad (6)$$

- n = number of turns per unit length
- Field inside is uniform

[Diagram comparing field patterns of loop and solenoid]

Magnetic Flux

Magnetic Flux Definition

$$\Phi = BA \cos \theta \quad (7)$$

- B = magnetic field strength (T)
- A = area (m^2)
- θ = angle between \vec{B} and area normal
- Units: $\text{T} \cdot \text{m}^2$ or weber (Wb)
- Flux measures the amount of magnetic field passing through an area

[Diagram illustrating magnetic flux through a loop]

Faraday's Law of Induction

Faraday's Law

$$\text{emf} = -N \frac{\Delta\Phi}{\Delta t} \quad (8)$$

- emf = induced electromotive force (voltage)
- N = number of turns in coil
- $\Delta\Phi/\Delta t$ = rate of change of magnetic flux
- Minus sign represents Lenz's law
- Electromagnetic induction: process of inducing emf through changing magnetic flux

Lenz's Law

Lenz's Law

The induced emf creates a current that produces a magnetic field that opposes the change in flux that produced it.

- Conservation of energy principle
- Determines direction of induced current
- Represented by minus sign in Faraday's law

[Diagram showing Lenz's law - induced current creating opposing magnetic field]

Motional Emf

Motional Emf Formula

$$\text{emf} = Blv \quad (B, l, \text{ and } v \text{ perpendicular}) \quad (9)$$

- B = magnetic field strength (T)
- l = length of conductor (m)
- v = velocity (m/s)
- Special case of Faraday's law
- Induced when conductor moves through magnetic field

[Diagram of a conductor moving through a magnetic field]

Eddy Currents and Magnetic Damping

- **Eddy currents:** current loops induced in moving conductors
- Produced when conductors move through non-uniform magnetic fields
- **Magnetic damping:** drag force created by eddy currents
- Applications:
 - Electromagnetic brakes
 - Metal detectors
 - Induction stoves
 - Damping in moving-coil meters

[Diagram showing eddy currents in a conductor moving through a magnetic field]

Induced EMF in a Generator

$$\text{emf} = NAB\omega \sin \omega t \quad (10)$$

- N = number of turns
- A = area of coil (m^2)
- B = magnetic field strength (T)
- ω = angular velocity (rad/s)
- Peak emf: $\text{emf}_0 = NAB\omega$
- Converts mechanical energy to electrical energy

[Diagram of a simple AC generator]

Back EMF in Motors

- Motors are generators running in reverse
- Rotating coil in motor induces its own emf
- **Back emf**: induced emf that opposes the applied voltage
- Limits current through motor
- Proportional to motor's rotation speed
- Low back emf during startup → high current draw

[Diagram illustrating back emf in a motor]

Transformer Equations

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} \quad (11)$$

$$\frac{I_s}{I_p} = \frac{N_p}{N_s} \quad (12)$$

- Use induction to change voltage levels
- V_p , V_s = primary and secondary voltages
- N_p , N_s = primary and secondary turns
- I_p , I_s = primary and secondary currents
- Step-up: $N_s > N_p$, increases voltage
- Step-down: $N_s < N_p$, decreases voltage
- Power is conserved: $V_p I_p = V_s I_s$

[Diagram of transformer showing primary and secondary coils]

Electrical Safety Systems

Three-Wire System:

- Live/hot wire
- Neutral wire
- Ground wire
- Grounds appliance case

Circuit Breakers/Fuses:

- Interrupt excessive currents
- Prevent thermal hazards

GFI (Ground Fault Interrupter):

- Detects current imbalance
- Protects against shock
- Uses induction principles

Isolation Transformer:

- Insulates device from source
- Prevents ground loops

Self-Inductance

$$\text{emf} = -L \frac{\Delta I}{\Delta t} \quad (13)$$

- **Inductance:** property describing how effectively a device induces emf
- L = self-inductance (H, henry)
- $\Delta I / \Delta t$ = rate of current change (A/s)
- $1 \text{ H} = 1 \Omega \cdot \text{s}$
- Self-inductance of a solenoid: $L = \frac{\mu_0 N^2 A}{l}$
- Energy stored in inductor: $E_{ind} = \frac{1}{2} L I^2$

Current when turning on:

$$I = I_0(1 - e^{-t/\tau}) \quad (14)$$

- $I_0 = \frac{V}{R}$ is final current

Current when turning off:

$$I = I_0 e^{-t/\tau} \quad (15)$$

- Current rises to $0.632I_0$ in first time constant
- Current falls to $0.368I_0$ in first time constant

Time constant: $\tau = \frac{L}{R}$

[Graph showing current vs. time for RL circuit turning on and off]

Reactance in AC Circuits

Inductive Reactance:

$$X_L = 2\pi fL \quad (16)$$

- In inductors, voltage leads current by 90°
- Reactance increases with frequency

Capacitive Reactance:

$$X_C = \frac{1}{2\pi fC} \quad (17)$$

- In capacitors, voltage lags current by 90°
- Reactance decreases with frequency

[Phasor diagrams showing phase relationships between voltage and current]

Impedance in RLC Circuit

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \quad (18)$$

- **Impedance:** AC equivalent of resistance
- **Resonant frequency:** $f_0 = \frac{1}{2\pi\sqrt{LC}}$
- At resonance: $X_L = X_C$ and $Z = R$
- **Phase angle:** $\cos \phi = \frac{R}{Z}$
- **Average power:** $P_{ave} = I_{rms} V_{rms} \cos \phi$
- **Power factor:** $\cos \phi$ (ranges from 0 to 1)

[Graph showing impedance vs. frequency with resonance peak]

I Do: Force on a Moving Charge

Example Problem

An electron (charge $q = -1.6 \times 10^{-19}$ C) is moving at $v = 2.0 \times 10^7$ m/s perpendicular to a magnetic field of $B = 0.5$ T. Calculate the magnetic force on the electron.

$$F = |q|vB \sin \theta \quad (19)$$

$$= (1.6 \times 10^{-19} \text{ C})(2.0 \times 10^7 \text{ m/s})(0.5 \text{ T})(\sin 90) \quad (20)$$

$$= (1.6 \times 10^{-19})(2.0 \times 10^7)(0.5)(1) \quad (21)$$

$$= 1.6 \times 10^{-12} \text{ N} \quad (22)$$

Direction: Use RHR-1, but reverse direction since electron is negatively charged.

We Do: Circular Motion in Magnetic Field

Example Problem

A proton (mass $m = 1.67 \times 10^{-27}$ kg, charge $q = 1.6 \times 10^{-19}$ C) is moving at $v = 3.0 \times 10^6$ m/s perpendicular to a magnetic field of $B = 0.2$ T. Calculate the radius of its circular path.

$$r = \frac{mv}{qB} \quad (23)$$

$$= \frac{(1.67 \times 10^{-27} \text{ kg})(3.0 \times 10^6 \text{ m/s})}{(1.6 \times 10^{-19} \text{ C})(0.2 \text{ T})} \quad (24)$$

$$=? \quad (25)$$

Let's work through this together...

You Do: Faraday's Law Application

Example Problem

A 200-turn circular coil with area 0.25 m^2 is in a magnetic field that changes from 0.5 T to 0.8 T perpendicular to the coil over a time of 0.1 s . Calculate the magnitude of the induced emf.

$$\text{emf} = -N \frac{\Delta \Phi}{\Delta t} \quad (26)$$

$$= -N \frac{\Delta(BA \cos \theta)}{\Delta t} \quad (27)$$

$$=? \text{ V} \quad (28)$$

Try solving this problem yourself!

Key Equations

Magnetic Forces:

$$F = qvB \sin \theta \quad (29)$$

$$F = IlB \sin \theta \quad (30)$$

$$\tau = NIAB \sin \theta \quad (31)$$

Magnetic Fields:

$$B = \frac{\mu_0 I}{2\pi r} \text{ (straight wire)} \quad (32)$$

$$B = \frac{\mu_0 I}{2R} \text{ (loop center)} \quad (33)$$

$$B = \mu_0 nI \text{ (solenoid)} \quad (34)$$

Electromagnetic Induction:

$$\Phi = BA \cos \theta \quad (35)$$

$$\text{emf} = -N \frac{\Delta \Phi}{\Delta t} \quad (36)$$

$$\text{emf} = Blv \text{ (motional)} \quad (37)$$

AC Circuits:

$$X_L = 2\pi fL \quad (38)$$

$$X_C = \frac{1}{2\pi fC} \quad (39)$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \quad (40)$$

Key Concepts

- Magnetic fields exert forces on moving charges and current-carrying conductors
- The direction of magnetic forces and fields can be determined using right hand rules
- Changing magnetic fields induce emfs (electromagnetic induction)
- Lenz's law: induced effects oppose the change that caused them
- Applications include generators, motors, and transformers
- Inductors oppose changes in current
- In AC circuits, impedance combines resistance and reactance
- At resonance, inductive and capacitive reactances cancel

Thank You!

Questions?

Next class: Electromagnetic Waves