PHYS11 CH: 22-23

Magnetism and Electromagnetic Induction

Mr. Gullo

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Outline

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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

Electromagnets:

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

[Image showing magnetic domains in a ferromagnetic material]

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Force on a Moving Charge

Magnetic Force Formula

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

- 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

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

- 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 a Current Loop

$$\tau = NIAB \sin\theta \tag{3}$$

- 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]

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Magnetic Fields Produced by Currents

Magnetic Field from a Long Straight Wire

$$B = \frac{\mu_0 I}{2\pi r} \tag{4}$$

- $\mu_0 = 4\pi \times 10^{-7}$ T·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:

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

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

Solenoid:

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

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

[Diagram comparing field patterns of loop and solenoid]

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Magnetic Flux

Magnetic Flux Definition

$$\Phi = BA\cos\theta \tag{7}$$

- B = magnetic field strength (T)
- A = area (m^2)
- θ = angle between $\vec{B}$ and area normal
- Units: $T{\cdot}m^2$ 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

$$\text{emf} = -N\frac{\Delta\Phi}{\Delta t} \tag{8}$$

- 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

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

- 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]

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Induced EMF in a Generator

$$\text{emf} = NAB\omega \sin \omega t \tag{10}$$

- 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 $\rightarrow$ high current draw

[Diagram illustrating back emf in a motor]

Transformers

Transformer Equations

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} \tag{11}$$

$$\frac{I_s}{I_p} = \frac{N_p}{N_s} \tag{12}$$

- 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

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Self-Inductance

$$\text{emf} = -L\frac{\Delta I}{\Delta t} \tag{13}$$

- **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 H = 1 Ω·s
- Self-inductance of a solenoid: $L = \frac{\mu_0 N^2 A}{l}$
- Energy stored in inductor: $E_{ind} = \frac{1}{2}LI^2$

RL Circuits

Current when turning on:

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

Current when turning off:

$$I = I_0 e^{-t/\tau} \tag{15}$$

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

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

- $I_0 = \frac{V}{R}$ is final current
- Current rises to $0.632 I_0$ in first time constant
- Current falls to $0.368 I_0$ in first time constant

Reactance in AC Circuits

Inductive Reactance:

$$X_L = 2\pi f L \tag{16}$$

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

Capacitive Reactance:

$$X_C = \frac{1}{2\pi f C} \tag{17}$$

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

[Phasor diagrams showing phase relationships between voltage and current]

RLC Series Circuits

Impedance in RLC Circuit

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

- **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]

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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.

$$
\begin{aligned}
F &= |q|vB\sin\theta && (19)\\
&= (1.6 \times 10^{-19}\ \text{C})(2.0 \times 10^{7}\ \text{m/s})(0.5\ \text{T})(\sin 90) && (20)\\
&= (1.6 \times 10^{-19})(2.0 \times 10^{7})(0.5)(1) && (21)\\
&= 1.6 \times 10^{-12}\ \text{N} && (22)
\end{aligned}
$$

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.

$$r = \frac{mv}{qB} \tag{23}$$

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

$$= ? \tag{25}$$

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.

$$\text{emf} = -N\frac{\Delta\Phi}{\Delta t} \tag{26}$$

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

$$=?\ \text{V} \tag{28}$$

Try solving this problem yourself!

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Key Equations

Magnetic Forces:

$$F = qvB\sin\theta \tag{29}$$
$$F = IlB\sin\theta \tag{30}$$
$$\tau = NIAB\sin\theta \tag{31}$$

Magnetic Fields:

$$B = \frac{\mu_0 I}{2\pi r} \text{ (straight wire)} \tag{32}$$
$$B = \frac{\mu_0 I}{2R} \text{ (loop center)} \tag{33}$$
$$B = \mu_0 nI \text{ (solenoid)} \tag{34}$$

Electromagnetic Induction:

$$\Phi = BA\cos\theta \tag{35}$$
$$\text{emf} = -N\frac{\Delta\Phi}{\Delta t} \tag{36}$$
$$\text{emf} = Blv \text{ (motional)} \tag{37}$$

AC Circuits:

$$X_L = 2\pi fL \tag{38}$$
$$X_C = \frac{1}{2\pi fC} \tag{39}$$
$$Z = \sqrt{R^2 + (X_L - X_C)^2} \tag{40}$$

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