PHYS11 CH: 5.5, 13, 14

Oscillations, Waves, and Sound Physics

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Outline

Learning Objectives

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

- Define and describe simple harmonic motion and its key parameters
- Identify and explain different types of waves and their properties
- Understand wave interactions including superposition and interference
- Apply wave principles to sound phenomena
- Solve problems involving wave speed, frequency, and wavelength
- Explain resonance and calculate resonant frequencies

Simple Harmonic Motion (SHM)

- An **oscillation** is a back and forth motion between two points
- **Periodic motion** is a repetitious oscillation
- **Period (T)**: Time for one complete oscillation
- **Frequency (f)**: Number of oscillations per unit time

$$f = \frac{1}{T} \tag{1}$$

- An oscillation may create a **wave**, which propagates from its source

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Hooke's Law and SHM

The simplest oscillations are described by Hooke's Law:

$$F = -kx \tag{2}$$

where:

- F is the restoring force
- k is the spring constant
- x is the displacement from equilibrium

For a spring-mass system or simple pendulum (small angle):

$$\text{Period in SHM: } T = 2\pi\sqrt{\frac{m}{k}} \tag{3}$$

$$\text{Frequency in SHM: } f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{4}$$

$$\text{Period of pendulum: } T = 2\pi\sqrt{\frac{L}{g}} \tag{5}$$

Types of Waves

Definition

A **wave** is a disturbance that moves from the point of creation and carries energy but not mass.

Based on medium requirement:

- **Mechanical waves** must travel through a medium
  - Sound waves
  - Water waves
  - Earthquake waves
- **Non-mechanical waves** can travel through vacuum
  - Light waves

Based on disturbance direction:

- **Transverse waves**: Disturbance perpendicular to propagation
- **Longitudinal waves**: Disturbance parallel to propagation

Based on duration:

- **Periodic waves**: Repeat for several cycles
- **Pulse waves**: One or few crests, sudden disturbance

Wave Properties

- **Wavelength (λ)**: Distance between adjacent identical parts of the wave
- **Amplitude**: Maximum displacement from equilibrium
- **Period (T)**: Time for one complete wave cycle
- **Frequency (f)**: Number of waves per unit time

$$f = \frac{1}{T} \tag{6}$$

- **Wave velocity (v_w)**: Speed at which wave moves

$$v_w = \frac{\lambda}{T} \text{ or } v_w = f\lambda \tag{7}$$

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Key Equations for Wave Motion

Wave Properties: Speed, Amplitude, Frequency, and Period

$$\text{Wave velocity: } v_w = \frac{\lambda}{T} \text{ or } v_w = f\lambda \tag{8}$$

$$\text{Period: } T = \frac{1}{f} \tag{9}$$

$$\text{Frequency: } f = \frac{1}{T} \tag{10}$$

- In a given medium at a specific temperature (or density), the speed of a wave is the same for all frequencies and wavelengths
- The relationship between wave velocity, frequency, and wavelength applies to all types of waves

Superposition and Interference

Principle of Superposition

When two or more waves overlap, the resultant displacement at any point is the algebraic sum of the displacements of the individual waves.

phys11-waves-interference-constructive-destructive.jpg

Constructive Interference

- Occurs when waves are in phase
- Amplitudes add together
- Results in a larger amplitude

Destructive Interference

- Occurs when waves are out of phase
- Amplitudes subtract
- Results in a smaller or zero amplitude

Standing Waves

Definition

A **standing wave** is produced by the superposition of two identical waves traveling in opposite directions. It varies in amplitude but does not propagate.

- **Nodes**: Points where there is no motion
- **Antinodes**: Locations of maximum amplitude

Other Wave Interactions:

- **Reflection**: Wave changes direction
- **Inversion**: Wave reflects from a fixed end
- **Refraction**: Wave's path bends when passing between media with different densities

phys11-waves-standing-wa

Sound Wave Characteristics

Definition

Sound is a longitudinal mechanical wave created by a disturbance that is transmitted through a medium from its source outward.

- Sound waves require a medium to travel (cannot propagate in vacuum)
- The relationship of speed, frequency, and wavelength:

$$v = f\lambda \tag{11}$$

- The speed of sound depends on the medium
  - Air at 20°C: approximately 343 m/s
  - Water: approximately 1480 m/s
  - Steel: approximately 5960 m/s
- In a given medium at specific temperature/density, the speed of sound is the same for all frequencies

Sound Intensity and Sound Level

- **Sound intensity (I)**: Power per unit area

$$I = \frac{P}{A} = \frac{(\Delta p)^2}{2\rho v_w} \qquad (12)$$

where Δp is pressure variation, ρ is density, and v_w is wave speed

- **Sound intensity level** in decibels (dB):

$$\beta\ (\text{dB}) = 10 \log_{10}\left(\frac{I}{I_0}\right) \qquad (13)$$

where $I_0 = 10^{-12}$ W/m² (threshold of hearing)

Some typical sound levels:

- Whisper: 20 dB
- Normal conversation: 60 dB
- Busy traffic: 80 dB
- Threshold of pain: 120 dB
- Jet engine: 140 dB

Doppler Effect

A shift in the observed frequency of a sound due to motion of either the source or the observer.

For a moving source:

$$f_{obs} = f_s \left(\frac{v_w}{v_w \pm v_s} \right) \tag{14}$$

For a moving observer:

$$f_{obs} = f_s \left(\frac{v_w \pm v_{obs}}{v_w} \right) \tag{15}$$

Note: Use (+) when moving toward each other and (-) when moving apart

Sonic Boom

- Occurs when an object moves faster than sound
- Creates a shock wave
- Result of constructive interference

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Sound Interference Patterns

- Sound waves can interfere constructively or destructively
- **Beats**: Occur when waves of slightly different frequencies are superimposed
$$f_B = |f_1 - f_2| \tag{16}$$
- Beats are perceived as periodic variations in loudness
- Used in tuning musical instruments

Resonance in Air Columns

Natural Frequency

The frequency at which a system will oscillate if not affected by driving or damping forces.

Resonance

Occurs when a periodic force drives a harmonic oscillator at its natural frequency, resulting in maximum amplitude.

Tube closed at one end:

$$f_n = n\frac{v}{4L}, \ n = 1, 3, 5... \tag{17}$$

- Fundamental: $f_1 = \frac{v}{4L}$
- Only odd harmonics

Tube open at both ends:

$$f_n = n\frac{v}{2L}, \ n = 1, 2, 3... \tag{18}$$

- Fundamental: $f_1 = \frac{v}{2L}$
- All harmonics possible

phys11-waves-resonance-closed-tube.png

phys11-waves-resonance-closed-tube.png

"I do" - Wave Properties Example

Problem

A wave has a frequency of 40 Hz and a wavelength of 0.5 m. Calculate the wave velocity.

Solution

Given:

- Frequency $f = 40$ Hz
- Wavelength $\lambda = 0.5$ m

Using the wave velocity equation:

$$v_w = f\lambda \tag{19}$$

$$v_w = 40 \text{ Hz} \times 0.5 \text{ m} \tag{20}$$

$$v_w = 20 \text{ m/s} \tag{21}$$

"We do" - Speed of Sound Example

Problem

Sound travels at 343 m/s in air. If a sound wave has a frequency of 686 Hz, what is its wavelength?

Partial Solution

Given:

- Speed of sound $v = 343$ m/s
- Frequency $f = 686$ Hz

Using the wave velocity equation:

$$v = f\lambda \tag{22}$$

$$343 \text{ m/s} = 686 \text{ Hz} \times \lambda \tag{23}$$

Now, solve for λ...

"You do" - Sound Resonance Example

Problem

A tube open at both ends has a length of 0.85 m. If the speed of sound in air is 343 m/s, what are the frequencies of the fundamental and first two overtones?

Approach

1. Identify the type of resonator (open at both ends) 2. Recall the formula for resonant frequencies in an open tube 3. Calculate the fundamental frequency 4. Calculate the frequencies of the first two overtones

Try it yourself! We'll review the solution in a moment.

"You do" - Sound Resonance Solution

Solution

For a tube open at both ends:

$$f_n = n\frac{v}{2L}, \; n = 1, 2, 3... \tag{24}$$

Given:

- Length $L = 0.85$ m
- Speed of sound $v = 343$ m/s

Fundamental frequency ($n = 1$):

$$f_1 = \frac{343 \text{ m/s}}{2 \times 0.85 \text{ m}} = 201.8 \text{ Hz} \tag{25}$$

First overtone ($n = 2$): $f_2 = 2f_1 = 403.5$ Hz
Second overtone ($n = 3$): $f_3 = 3f_1 = 605.3$ Hz

Key Concepts Review

Simple Harmonic Motion

- Oscillations and periodic motion
- Period and frequency relationship
- Hooke's Law systems

Waves

- Types: mechanical/non-mechanical
- Types: transverse/longitudinal
- Properties: wavelength, amplitude, frequency
- Speed-wavelength-frequency relationship

Wave Interactions

- Superposition principle
- Constructive/destructive interference
- Standing waves, nodes, antinodes

Sound

- Longitudinal mechanical wave
- Intensity and sound level
- Doppler effect
- Resonance and harmonics

Essential Equations

Simple Harmonic Motion

$$F = -kx \tag{26}$$

$$T = 2\pi\sqrt{\frac{m}{k}} \tag{27}$$

$$T_{pendulum} = 2\pi\sqrt{\frac{L}{g}} \tag{28}$$

Wave Properties

$$v_w = \frac{\lambda}{T} \text{ or } v_w = f\lambda \tag{29}$$

$$T = \frac{1}{f} \tag{30}$$

Sound Intensity

$$I = \frac{P}{A} = \frac{(\Delta p)^2}{2\rho v_w} \tag{31}$$

$$\beta \text{ (dB)} = 10\log_{10}\left(\frac{I}{I_0}\right) \tag{32}$$

Resonance

$$f_B = |f_1 - f_2| \tag{33}$$

$$f_n = n\frac{v}{4L},\; n = 1, 3, 5\ldots \text{ (closed)} \tag{34}$$

$$f_n = n\frac{v}{2L},\; n = 1, 2, 3\ldots \text{ (open)} \tag{35}$$

Connecting the Concepts

- Simple harmonic motion creates oscillations
- Oscillations can generate waves
- Waves transport energy without transporting matter
- Sound is a longitudinal mechanical wave
- Wave properties (speed, frequency, wavelength) apply to all wave types
- Wave interactions explain phenomena like resonance and interference
- Understanding these principles helps explain everyday phenomena:
  - Musical instruments
  - Hearing
  - Doppler radar
  - Medical ultrasound
  - Noise cancellation

Thank You!

Questions?