Preview

- Objectives
- The Production of Sound Waves
- Frequency of Sound Waves
- The Doppler Effect
Objectives

- **Explain** how sound waves are produced.
- **Relate** frequency to pitch.
- **Compare** the speed of sound in various media.
- **Relate** plane waves to spherical waves.
- **Recognize** the Doppler effect, and **determine** the direction of a frequency shift when there is relative motion between a source and an observer.
Sound Waves

Click below to watch the Visual Concept.

Visual Concept
Every sound wave begins with a **vibrating object**, such as the vibrating prong of a tuning fork.

A **compression** is the region of a longitudinal wave in which the density and pressure are at a maximum.

A **rarefaction** is the region of a longitudinal wave in which the density and pressure are at a minimum.
The Production of Sound Waves, continued

- Sound waves are **longitudinal**.
- The simplest longitudinal wave produced by a vibrating object can be represented by a **sine curve**.
- In the diagram, the **crests** of the sine curve correspond to **compressions**, and the **troughs** correspond to **rarefactions**.
Frequency of Sound Waves

- As discussed earlier, **frequency** is defined as the number of cycles per unit of time.

- Sound waves that the average human ear can hear, called **audible** sound waves, have frequencies between **20 and 20,000 Hz**.

- Sound waves with frequencies **less than 20 Hz** are called **infrasonic** waves.

- Sound waves with frequencies **above 20,000 Hz** are called **ultrasonic** waves.
Chapter 12

Section 1 Sound Waves

Frequency of Sound Waves

Click below to watch the Visual Concept.

Visual Concept
Frequency and Pitch

• The **frequency** of an audible sound wave determines how **high** or **low** we perceive the sound to be, which is known as **pitch**.

• As the frequency of a sound wave **increases**, the pitch **rises**.

• The frequency of a wave is an objective quantity that can be measured, while pitch refers to how different frequencies are perceived by the human ear.
Frequency and Pitch

Click below to watch the Visual Concept.

Visual Concept
The Speed of Sound

- The speed of sound depends on the **medium**.
  - Because waves consist of particle vibrations, the speed of a wave depends on how quickly one particle can transfer its motion to another particle.
  - For example, sound waves generally travel faster through solids than through gases because the molecules of a solid are closer together than those of a gas are.
- The speed of sound also depends on the **temperature** of the medium. This is most noticeable with gases.
# The Speed of Sound in Various Media

<table>
<thead>
<tr>
<th>Medium</th>
<th>( v ) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gases</strong></td>
<td></td>
</tr>
<tr>
<td>air ((0^\circ C))</td>
<td>331</td>
</tr>
<tr>
<td>air ((25^\circ C))</td>
<td>346</td>
</tr>
<tr>
<td>air ((100^\circ C))</td>
<td>366</td>
</tr>
<tr>
<td>helium ((0^\circ C))</td>
<td>972</td>
</tr>
<tr>
<td>hydrogen ((0^\circ C))</td>
<td>1290</td>
</tr>
<tr>
<td>oxygen ((0^\circ C))</td>
<td>317</td>
</tr>
<tr>
<td><strong>Liquids at 25^\circ C</strong></td>
<td></td>
</tr>
<tr>
<td>methyl alcohol</td>
<td>1140</td>
</tr>
<tr>
<td>sea water</td>
<td>1530</td>
</tr>
<tr>
<td>water</td>
<td>1490</td>
</tr>
<tr>
<td><strong>Solids</strong></td>
<td></td>
</tr>
<tr>
<td>aluminum</td>
<td>5100</td>
</tr>
<tr>
<td>copper</td>
<td>3560</td>
</tr>
<tr>
<td>iron</td>
<td>5130</td>
</tr>
<tr>
<td>lead</td>
<td>1320</td>
</tr>
<tr>
<td>vulcanized rubber</td>
<td>54</td>
</tr>
</tbody>
</table>
The Propagation of Sound Waves

- Sound waves propagate in three dimensions.
- Spherical waves can be represented graphically in two dimensions, as shown in the diagram.
- The circles represent the centers of compressions, called wave fronts.
- The radial lines perpendicular to the wave fronts are called rays.
- The sine curve used in our previous representation corresponds to a single ray.
At distances from the source that are great relative to the wavelength, we can approximate *spherical wave fronts* with *parallel planes*.

Such waves are called *plane waves*.

Plane waves can be treated as one-dimensional waves all traveling in the same direction.
Chapter 12
Section 1  Sound Waves

The Doppler Effect

Click below to watch the Visual Concept.
The Doppler Effect

- The **Doppler effect** is an observed change in frequency when there is **relative motion** between the source of waves and an observer.

- Because frequency determines pitch, the Doppler effect affects the **pitch** heard by each listener.

- Although the Doppler effect is most commonly experienced with sound waves, it is a phenomenon common to all waves, including electromagnetic waves, such as visible light.
Chapter 12

Section 2  Sound Intensity and Resonance

Preview

• Objectives
• Sound Intensity
• Forced Vibrations and Resonance
• The Human Ear
Objectives

- **Calculate** the intensity of sound waves.
- **Relate** intensity, decibel level, and perceived loudness.
- **Explain** why resonance occurs.
Sound Intensity

• As sound waves travel, energy is transferred from one molecule to the next. The rate at which this energy is transferred through a unit area of the plane wave is called the **intensity** of the wave.

• Because **power** \( (P) \) is defined as the rate of energy transfer, intensity can also be described in terms of power.

\[
\text{intensity} = \frac{\Delta E / \Delta t}{\text{area}} = \frac{P}{4\pi r^2}
\]

\[
\text{intensity} = \frac{\text{power}}{(4\pi)(\text{distance from the source})^2}
\]
Sound Intensity, continued

• Intensity has units of **watt per square meter (W/m²)**.

• The intensity equation shows that the **intensity decreases** as the **distance (r) increases**.

• This occurs because the same amount of energy is spread over a larger area.
Sound Intensity, *continued*

- Human hearing depends on both the **frequency** and the **intensity** of sound waves.

- Sounds in the middle of the spectrum of frequencies can be heard more easily (at lower intensities) than those at lower and higher frequencies.
Sound Intensity, continued

- The **intensity** of a wave approximately determines its perceived **loudness**.

- However, loudness is not directly proportional to intensity. The reason is that the sensation of loudness is approximately **logarithmic** in the human ear.

- **Relative intensity** is the ratio of the intensity of a given sound wave to the intensity at the threshold of hearing.
Sound Intensity, *continued*

- Because of the logarithmic dependence of perceived loudness on intensity, using a number equal to **10 times the logarithm of the relative intensity** provides a good indicator for human perceptions of loudness.

- This is referred to as the **decibel level**.

- A dimensionless unit called the **decibel (dB)** is used for values on this scale.
### Conversion of Intensity to Decibel Level

<table>
<thead>
<tr>
<th>Intensity (W/m²)</th>
<th>Decibel level (dB)</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.0 \times 10^{-12}$</td>
<td>0</td>
<td>threshold of hearing</td>
</tr>
<tr>
<td>$1.0 \times 10^{-11}$</td>
<td>10</td>
<td>rustling leaves</td>
</tr>
<tr>
<td>$1.0 \times 10^{-10}$</td>
<td>20</td>
<td>quiet whisper</td>
</tr>
<tr>
<td>$1.0 \times 10^{-9}$</td>
<td>30</td>
<td>whisper</td>
</tr>
<tr>
<td>$1.0 \times 10^{-8}$</td>
<td>40</td>
<td>mosquito buzzing</td>
</tr>
<tr>
<td>$1.0 \times 10^{-7}$</td>
<td>50</td>
<td>normal conversation</td>
</tr>
<tr>
<td>$1.0 \times 10^{-6}$</td>
<td>60</td>
<td>air conditioning at 6 m</td>
</tr>
<tr>
<td>$1.0 \times 10^{-5}$</td>
<td>70</td>
<td>vacuum cleaner</td>
</tr>
<tr>
<td>$1.0 \times 10^{-4}$</td>
<td>80</td>
<td>busy traffic, alarm clock</td>
</tr>
<tr>
<td>$1.0 \times 10^{-3}$</td>
<td>90</td>
<td>lawn mower</td>
</tr>
<tr>
<td>$1.0 \times 10^{-2}$</td>
<td>100</td>
<td>subway, power motor</td>
</tr>
<tr>
<td>$1.0 \times 10^{-1}$</td>
<td>110</td>
<td>auto horn at 1 m</td>
</tr>
<tr>
<td>$1.0 \times 10^{0}$</td>
<td>120</td>
<td>threshold of pain</td>
</tr>
<tr>
<td>$1.0 \times 10^{1}$</td>
<td>130</td>
<td>thunderclap, machine gun</td>
</tr>
<tr>
<td>$1.0 \times 10^{3}$</td>
<td>150</td>
<td>nearby jet airplane</td>
</tr>
</tbody>
</table>
Forced Vibrations and Resonance

- If one of the pendulums is set in motion, its vibrations are transferred by the rubber band to the other pendulums, which will also begin vibrating. This is called a **forced vibration**.

- Each pendulum has a **natural frequency** based on its length.
Forced Vibrations and Resonance, continued

- **Resonance** is a phenomenon that occurs when the frequency of a force applied to a system matches the **natural frequency** of vibration of the system, resulting in a **large amplitude of vibration**.

- If one blue pendulum is set in motion, only the other blue pendulum, whose length is the same, will eventually resonate.
Chapter 12

Section 2  Sound Intensity and Resonance

Resonance

Click below to watch the Visual Concept.
The Human Ear

- The human ear is divided into three sections—outer, middle, and inner.
- Sound waves travel through the three regions of the ear and are then transmitted to the brain as impulses through nerve endings on the basilar membrane.
Chapter 12

Section 2 Sound Intensity and Resonance

Human Hearing

Click below to watch the Visual Concept.
Chapter 12
Section 3  Harmonics

Preview

- Objectives
- Standing Waves on a Vibrating String
- Standing Waves in an Air Column
- Sample Problem
- Timbre
- Beats
Chapter 12

Section 3 Harmonics

Objectives

• **Differentiate** between the harmonic series of open and closed pipes.

• **Calculate** the harmonics of a vibrating string and of open and closed pipes.

• **Relate** harmonics and timbre.

• **Relate** the frequency difference between two waves to the number of beats heard per second.
Chapter 12 Section 3  Harmonics

Fundamental Frequency

Click below to watch the Visual Concept.

Visual Concept
Standing Waves on a Vibrating String

- The vibrations on the string of a musical instrument usually consist of many standing waves, each of which has a different wavelength and frequency.
- The greatest possible wavelength on a string of length $L$ is $\lambda = 2L$.
- The fundamental frequency, which corresponds to this wavelength, is the lowest frequency of vibration.

$$f_1 = \frac{v}{\lambda_1} = \frac{v}{2L}$$
Harmonic Series

Click below to watch the Visual Concept.
Standing Waves on a Vibrating String, continued

• Each harmonic is an integral multiple of the fundamental frequency.

• The harmonic series is a series of frequencies that includes the fundamental frequency and integral multiples of the fundamental frequency.

Harmonic Series of Standing Waves on a Vibrating String

\[ f_n = \frac{n \cdot \frac{v}{2L}}{n = 1, 2, 3, \ldots} \]

frequency = harmonic number \( \times \) \( \frac{\text{speed of waves on the string}}{2\text{(length of the vibrating string)}} \)
Chapter 12

Section 3 Harmonics

The Harmonic Series

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Wavelength ($\lambda$)</th>
<th>Frequency ($f$)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental</td>
<td>$\lambda_1 = 2L$</td>
<td>$f_1$</td>
<td>frequency, or first harmonic</td>
</tr>
<tr>
<td>Second</td>
<td>$\lambda_2 = L$</td>
<td>$f_2 = 2f_1$</td>
<td>second harmonic</td>
</tr>
<tr>
<td>Third</td>
<td>$\lambda_3 = \frac{2}{3}L$</td>
<td>$f_3 = 3f_1$</td>
<td>third harmonic</td>
</tr>
<tr>
<td>Fourth</td>
<td>$\lambda_4 = \frac{1}{2}L$</td>
<td>$f_4 = 4f_1$</td>
<td>fourth harmonic</td>
</tr>
</tbody>
</table>
Standing Waves in an Air Column

- If **both ends** of a pipe are **open**, there is an antinode at each end.

- In this case, **all harmonics are present**, and the earlier equation for the harmonic series of a vibrating string can be used.

**Harmonic Series of a Pipe Open at Both Ends**

\[ f_n = n \frac{v}{2L} \quad n = 1, 2, 3, \ldots \]

\[ \text{frequency} = \text{harmonic number} \times \frac{\text{(speed of sound in the pipe)}}{2 \times \text{(length of vibrating air column)}} \]
Standing Waves in an Air Column, continued

• If one end of a pipe is closed, there is a node at that end.
• With an antinode at one end and a node at the other end, a different set of standing waves occurs.
• In this case, only odd harmonics are present.

Harmonic Series of a Pipe Closed at One End

\[ f_n = n \frac{v}{4L} \quad n = 1, 3, 5, \ldots \]

frequency = harmonic number × \( \frac{\text{speed of sound in the pipe}}{4\times\text{length of vibrating air column}} \)
Chapter 12

Section 3  Harmonics

Harmonics of Open and Closed Pipes

Harmonics in an open-ended pipe

\[ \lambda_1 = 2L \]
\[ f_1 = \frac{v}{2L} \]

\[ \lambda_2 = L \]
\[ f_2 = \frac{v}{L} = 2f_1 \]

\[ \lambda_3 = \frac{2}{3}L \]
\[ f_3 = \frac{v}{2L} = 3f_1 \]

Harmonics in a pipe closed at one end

\[ \lambda_1 = 4L \]
\[ f_1 = \frac{v}{4L} \]

\[ \lambda_3 = \frac{4}{3}L \]
\[ f_3 = \frac{v}{4L} = 3f_1 \]

\[ \lambda_5 = \frac{4}{5}L \]
\[ f_5 = \frac{v}{4L} = 5f_1 \]
Sample Problem

Harmonics

What are the first three harmonics in a 2.45 m long pipe that is open at both ends? What are the first three harmonics when one end of the pipe is closed? Assume that the speed of sound in air is 345 m/s.

1. Define
   Given:
   \[ L = 2.45 \text{ m} \quad \text{and} \quad v = 345 \text{ m/s} \]
   Unknown:
   Case 1: \( f_1, f_2, f_3 \)  
   Case 2: \( f_1, f_3, f_5 \)
Sample Problem

2. Plan

Choose an equation or situation:

Case 1:

\[ f_n = n \frac{v}{2L} \quad n = 1, 2, 3, \ldots \]

Case 2:

\[ f_n = n \frac{v}{4L} \quad n = 1, 3, 5, \ldots \]

In both cases, the second two harmonics can be found by multiplying the harmonic numbers by the fundamental frequency.
Sample Problem

3. Calculate
Substitute the values into the equation and solve:
Case 1:

\[ f_1 = n \frac{v}{2L} = (1) \left( \frac{345 \text{ m/s}}{2(2.45 \text{ m})} \right) = 70.4 \text{ Hz} \]

The next two harmonics are the second and third:

\[ f_2 = 2f_1 = (2)(70.4 \text{ Hz}) = 141 \text{ Hz} \]
\[ f_3 = 3f_1 = (3)(70.4 \text{ Hz}) = 211 \text{ Hz} \]
Sample Problem

3. **Calculate, continued**

Case 2:

\[ f_1 = n \frac{v}{4L} = (1) \left( \frac{345 \text{ m/s}}{4(2.45 \text{ m})} \right) = 35.2 \text{ Hz} \]

The next two harmonics are the third and the fifth:

\[ f_3 = 3f_1 = (3)(35.2 \text{ Hz}) = 106 \text{ Hz} \]
\[ f_5 = 5f_1 = (5)(35.2 \text{ Hz}) = 176 \text{ Hz} \]

**Tip:** Use the correct harmonic numbers for each situation. For a pipe open at both ends, \( n = 1, 2, 3, \) etc. For a pipe closed at one end, only odd harmonics are present, so \( n = 1, 3, 5, \) etc.
Sample Problem

4. Evaluate

In a pipe open at both ends, the first possible wavelength is \(2L\); in a pipe closed at one end, the first possible wavelength is \(4L\). Because frequency and wavelength are inversely proportional, the fundamental frequency of the open pipe should be twice that of the closed pipe, that is, \(70.4 = (2)(35.2)\).
Chapter 12

Section 3  Harmonics

Timbre

Click below to watch the Visual Concept.

Visual Concept
Timbre is the musical quality of a tone resulting from the combination of harmonics present at different intensities.

A clarinet sounds different from a viola because of differences in timbre, even when both instruments are sounding the same note at the same volume.

The rich harmonics of most instruments provide a much fuller sound than that of a tuning fork.
Harmonics of Musical Instruments

Tuning fork

Clarinet

Viola
Chapter 12

Section 3  Harmonics

Beats

Click below to watch the Visual Concept.

Visual Concept
Beats

- When two waves of slightly different frequencies interfere, the interference pattern varies in such a way that a listener hears an alternation between loudness and softness.

- The variation from soft to loud and back to soft is called a beat.

- In other words, a beat is the periodic variation in the amplitude of a wave that is the superposition of two waves of slightly different frequencies.
Chapter 12

Section 3  Harmonics

Beats

Destructive interference

Constructive interference

Destructive interference