Chapter 14

Sound Waves

• Sound is longitudinal pressure (compression) waves

• Range of hearing: 20 Hz to 20,000 Hz

FREQUENCY DEMO

Sound Waves

Liquids and Gases: $B$ is bulk modulus, $\rho$ is mass/volume

Solids: $Y$ is Young's modulus

$v = \sqrt{\frac{B}{\rho}}$

$\nu = \sqrt{\frac{Y}{\rho}}$

$\nu_{air} = (331 \frac{m}{s}) \sqrt{\frac{T}{273 K}}$

331 m/s is $v$ at 0° C;
$T$ is the absolute temperature.

Example 14.1

John Brown hits a steel railroad rail with a hammer. Betsy Brown, standing one mile down the track, hears the bang through the cool 32 °F air while her twin sister Boopsie is lying next to her and hears the bang through the steel by placing her ear on the track.

$Y_{steel}=2.0\times10^{11}$ Pa, $\rho_{steel}=7850$ kg/m³

What is the time difference between the moments when Betsy and Boopsie hear the bang?

$4.54$ s

Intensity of Sound Waves

$I = \frac{\Delta F}{A \Delta t} = \frac{P}{A}$

Power

Area

SI units are $W/m^2$

Intensity is proportional to square of amplitude (pressure modulation)

Intensity Range for Human Hearing

Threshold of Hearing

$10^{-12}$ W/m²

$\Delta P \sim 10^{-10}$ atm

Threshold of Pain

$1.0$ W/m²
Decibel Scale

Sensation is logarithmic

\[ \beta = 10 \log_{10} \frac{I}{I_0} \]

\[ I = I_0 10^{\beta/10} \]

- \( I_0 \) is threshold of hearing (0 dB)
- Threshold of Pain is therefore 120 dB

<table>
<thead>
<tr>
<th>Source of Sound</th>
<th>( \beta ) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nearby jet airplane</td>
<td>150</td>
</tr>
<tr>
<td>Jackhammer, machine gun</td>
<td>130</td>
</tr>
<tr>
<td>Siren, rock concert</td>
<td>120</td>
</tr>
<tr>
<td>Subsw, power mower</td>
<td>100</td>
</tr>
<tr>
<td>Busy traffic</td>
<td>80</td>
</tr>
<tr>
<td>Vacuum cleaner</td>
<td>70</td>
</tr>
<tr>
<td>Normal conversation</td>
<td>50</td>
</tr>
<tr>
<td>Mosquito buzzing</td>
<td>40</td>
</tr>
<tr>
<td>Whisper</td>
<td>30</td>
</tr>
<tr>
<td>Rustling leaves</td>
<td>10</td>
</tr>
<tr>
<td>Threshold of hearing</td>
<td>0</td>
</tr>
</tbody>
</table>

Intensity vs. Intensity Level

- INTENSITY is \( P/A \), W/m²
- INTENSITY LEVEL is in decibels (dimensionless)

Example 14.2

A noisy machine in a factory produces a sound with a level of 80 dB. How many machines can the factory house without exceeding the 100-dB limit?

a) 12.5 machines
b) 20 machines
c) 100 machines

Spherical Waves

Energy propagates equally in all directions

\[ I = \frac{P}{4\pi r^2} \Rightarrow \frac{I_1}{I_2} = \frac{r_2^2}{r_1^2} \]

Example 14.3 (skip)

A train sounds its horn as it approaches an intersection. The horn can just be heard at a level of 50 dB by an observer 10 km away. Treating the horn as a point source and neglect any absorption of sound by the air or ground,

a) What is the average power generated by the horn?
   a) 126 W
b) What intensity level of the horn’s sound is observed by someone waiting at an intersection 50 m from the train?
   b) 96 dB
**Example 14.4**

Bozo Bob buys a 20-W train whistle and figures out that he won't have any trouble standing 2 meters from the whistle since his stereo speakers are rated at 100 W and he has little trouble with the speakers turned all the way up. What is the intensity level of the whistle?

116 dB

**Doppler Effect**

A change in the frequency experienced by an observer due to motion of either the observer or the source.

**Example 14.5**

Mary is riding a roller coaster. Her mother who is standing on the ground behind her yells out to her at a frequency of 1000 Hz, but it sounds like 920 Hz. ($v=343$ m/s)

What is Mary's speed?

27.4 m/s
Example 14.6

An train has a brass band playing a song on a flatcar. As the train approaches the station at 21.4 m/s, a person on the platform hears a trumpet play a note at 3520 Hz. DATA: \( v_{\text{sound}} = 343 \text{ m/s} \)

a) What is the true frequency of the trumpet?  
   a) 3300 Hz

b) What is the wavelength of the sound?  
   b) 9.74 cm

c) If the trumpet plays the same note after passing the platform, what frequency would the person on the platform hear?  
   c) 3106 Hz
Example 14.7
At rest, a car’s horn sounds the note A (440 Hz). The horn is sounded while the car moves down the street. A bicyclist moving in the same direction at 10 m/s hears a frequency of 415 Hz.
DATA: $v_{\text{sound}} = 343$ m/s.

What is the speed of the car? (Assume the cyclist is behind the car) 31.3 m/s

Example 14.8a
A train has a whistle with a frequency of a 1000 Hz, as measured when the both the train and observer are stationary. For a train moving in the positive $x$ direction, which observer hears the highest frequency when the train is at position $x=0$.

Observer A has velocity $V_A > 0$ and has position $X_A > 0$.
Observer B has velocity $V_B > 0$ and has position $X_B < 0$.
Observer C has velocity $V_C < 0$ and has position $X_C > 0$.
Observer D has velocity $V_D < 0$ and has position $X_D < 0$.

Example 14.8b
A train has a whistle with a frequency of a 1000 Hz, as measured when the both the train and observer are stationary. For a train moving in the positive $x$ direction, which observer hears the highest frequency when the train is at position $x=0$.

An observer with $V>0$ and position $X>0$ hears a frequency:

a) > 1000 Hz
b) < 1000 Hz
c) Can not be determined

Example 14.8c
A train has a whistle with a frequency of a 1000 Hz, as measured when the both the train and observer are stationary. For a train moving in the positive $x$ direction, which observer hears the highest frequency when the train is at position $x=0$.

An observer with $V>0$ and position $X<0$ hears a frequency:

a) > 1000 Hz
b) < 1000 Hz
c) Can not be determined

Example 14.8d
A train has a whistle with a frequency of a 1000 Hz, as measured when the both the train and observer are stationary. For a train moving in the positive $x$ direction, which observer hears the highest frequency when the train is at position $x=0$.

An observer with $V<0$ and position $X<0$ hears a frequency:

a) > 1000 Hz
b) < 1000 Hz
c) Can not be determined

Standing Waves
Consider a wave and its reflection:

\[
y_{\text{right}} = A \sin \left[ 2\pi \left( \frac{x}{\lambda} - \frac{ft}{\lambda} \right) \right]
= A \left\{ \sin \left( 2\pi \frac{x}{\lambda} \right) \cos 2\pi ft - \cos \left( 2\pi \frac{x}{\lambda} \right) \sin 2\pi ft \right\}
\]

\[
y_{\text{left}} = A \sin \left[ 2\pi \left( \frac{x}{\lambda} + \frac{ft}{\lambda} \right) \right]
= A \left\{ \sin \left( 2\pi \frac{x}{\lambda} \right) \cos 2\pi ft + \cos \left( 2\pi \frac{x}{\lambda} \right) \sin 2\pi ft \right\}
\]

\[
y_{\text{right}} + y_{\text{left}} = 2A \sin \left( 2\pi \frac{x}{\lambda} \right) \cos 2\pi ft
\]
Standing Waves

\[ y_{\text{right}} + y_{\text{left}} = 2A \sin \left( \frac{2\pi x}{\lambda} \right) \cos 2\pi ft \]

- Factorizes into x-piece and t-piece
- Always ZERO at \( x=0 \) or \( x=m\lambda/2 \)

Resonances

Integral number of half wavelengths in length \( L \)

\[ \frac{\lambda}{2} = L \]

Nodes and anti-nodes

- A node is a minimum in the pattern
- An antinode is a maximum

Example 14.9

A cello string vibrates in its fundamental mode with a frequency of 220 vibrations/s. The vibrating segment is 70.0 cm long and has a mass of 1.20 g.

a) Find the tension in the string

b) Determine the frequency of the string when it vibrates in three segments.
Example 14.10

An organ pipe of length 1.5 m is open at one end and closed at the other. What are the lowest two harmonic frequencies?

DATA: Speed of sound = 343 m/s

57.2 Hz, 171.5 Hz

Beat Frequency Derivation

After time $T_{\text{beat}}$, two sounds will differ by one complete cycle.

$$n_1 - n_2 = 1$$

$$f_1 T_{\text{beat}} - f_2 T_{\text{beat}} = 1$$

$$T_{\text{beat}} = \frac{1}{f_1 - f_2}$$

$$f_{\text{beat}} = \frac{1}{T_{\text{beat}}}$$

$$f_{\text{beat}} = f_1 - f_2$$

Beats Demo

Standing Waves in Air Columns
Example 14.11

An organ pipe (open at one end and closed at the other) is designed to have a fundamental frequency of 440 Hz. Assuming the speed of sound is 343 m/s,

a) What is the length of the pipe?  
   a) 19.5 cm

b) What is the frequency of the next harmonic?  
   b) 1320 Hz

Example 14.12

A pair of speakers separated by 1.75 m are driven by the same oscillator at a frequency of 686 Hz. An observer starts at one of the speakers and walks on a path that is perpendicular to the separation of the two speakers. (Assume \( v_{\text{sound}} = 343 \text{ m/s} \))

a) What is the position of the last intensity maximum?  
   a) 2.81 m

b) What is the position of the last intensity minimum?  
   b) 6.00 m

c) What is the position of the first intensity  
   c) 27 cm