Chapter 13

Sound
• Sounds waves are an important example of wave motion
• Sound is central to hearing, speech, music and many other daily activities
• Characteristics of sound waves that will be considered include
  • How they are generated
  • How they propagate
  • How they are detected by the ear
Sound In Air

- Sound waves can travel through gases, liquids, and solids
- Gas molecules are in constant random motion
- A typical air molecule at room temperature has a speed of 500 m/s
  - Call this the “background velocity, ”$v_0$
  - The direction is different for every molecule
Sound in Air, 2

- The loudspeaker generates a sound wave in the air
- When the speaker is off, the density of the air molecules is the same throughout the tube

No sound: Air has uniform density.
Sound in Air, 3

- When the loudspeaker is on, its diaphragm moves back and forth.
- As it moves, it collides with air molecules.
- It gives the air molecules a small extra velocity, \( \mathbf{v}_{molecule} \).
- At some times, this velocity is directed toward the right and at other times toward the left.

The molecular motion due to the sound wave \( \mathbf{v}_{molecule} \) is parallel to \( x \).
• This extra velocity is the velocity of the molecule, not the velocity of the wave
• Since the extra velocity is parallel to the direction of motion, this is a longitudinal wave
• Since the displacement alternates between +x and –x, the density of molecules is increased in some regions and decreased in others
• Oscillations in air density cause oscillations in the air pressure
• Sound can also be viewed as a pressure wave
The regions of high density and high pressure are called regions of \textit{condensation}.

The regions of low density and low pressure are called regions of \textit{rarefaction}.
Speed of Sound

- Adjacent regions of high pressure are separated by a distance equal to the wavelength
  - Adjacent regions of low pressure are also separated by the wavelength
- The speed of the sound wave is given by $v_{\text{sound}} = f \lambda$
- It is very important to distinguish between the velocity of the wave and the velocity of the particles within the medium
  - They are not the same

Section 13.1
Sound Waves in Other Media

- Sound traveling through liquids or solids is similar to air.
- The sound wave causes a displacement of the molecules in the solid or liquid parallel to the propagation direction.
- So sound is a longitudinal wave in solids and liquids as well as in gas.
- There can be no transverse waves in a gas or liquid.
  - There can be transverse waves in a solid.
Speed of Sound

- The speed of sound depends on the medium the wave is traveling through
  - See table 13.1
- In general, the speed of sound is fastest in solids and slowest in gases
- In general, the speed of sound can be expressed as
  \[
  V_{\text{sound}} = \sqrt{\frac{\text{stiffness}}{\text{density}}}
  \]
Speed of Sound, cont.

- A stiffer material generates a larger restoring force
  - Hooke’s Law
- This leads to larger particle accelerations
- This also leads to a larger speed of sound
- Solids are stiffer than liquids, and liquids are stiffer than gases
  - This explains the pattern of speeds
- The density factor indicates the less dense the material, the higher the speed
- A smaller mass has a greater acceleration for any given force and so the speed of the wave will be higher

Section 13.1
Speed of Sound – Equations

- The speed of sound in a solid is 
  \[ v_{\text{sound}} = \sqrt{\frac{Y}{\rho}} \]

- The speed of sound in a fluid is 
  \[ v_{\text{sound}} = \sqrt{\frac{B}{\rho}} \]

- The speed of sound in a gas depends on its temperature and pressure.
  - For air near room temperature and pressure, 
    \[ v_{\text{sound}} = 343 + 0.6 \ (T - 20^\circ \text{C}) \ \text{m/s} \]
    • T is in Celsius

Section 13.1
Speed and Frequency of Sound

- The general relationship for a wave, \( v = f \lambda \), holds.
- The speed of the sound wave is a function of the medium and is independent of the frequency and amplitude.
  - The frequency and amplitude depend on how the wave is generated.
- Frequency range of normal human hearing is 20 Hz to 20 kHz.
  - Sound waves below 20 Hz are called *infrasonic*.
  - Sound waves above 20 kHz are called *ultrasonic*.
Musical Tones

• A sound wave described by a single frequency is called a **pure tone**
• Most sounds are combinations of many pure tones
• Many sounds are a combination of frequencies that are harmonically related
  • A harmonic sequence is related to the fundamental frequency by $f_n = n \cdot f_1$
• One way to characterize a combination tone is by a property called **pitch**
  • Generally, the pitch of a pure tone is its frequency
  • With more complex sounds, the pitch is associated with the fundamental frequency

Section 13.1
Hearing

- When a sound wave reaches your ear, the pressure on the outside of your eardrum is the atmospheric pressure plus the oscillating sound pressure.
- On the inside of your eardrum, the pressure is equal to the atmospheric pressure.
- Generally, your eardrum is insensitive to atmospheric pressure, but detects the sound pressure.

\[ P_{\text{outside}} = P_{\text{atm}} + p \]

\[ P_{\text{inside}} = P_{\text{atm}} \]
Intensity and Amplitude

- The **intensity** of the sound wave equals the power carried by the wave per unit area of wave front.
- The intensity of a wave is proportional to the amplitude of the pressure oscillation.
  - \( I \propto p_{amp}^2 \)
- In many cases, sound waves propagate as spherical waves.
  - \( I \propto \frac{1}{r^2} \)
- Therefore, \( p_{amp} \propto \frac{1}{r} \)

Section 13.2
Decibels

- The sensitivity of the ear depends on the frequency of the sound.
- In the most favorable frequency range, the ear can detect intensities as small as about $10^{-12} \text{ W/m}^2$.
- A more convenient unit, the **decibel** (dB), is often used to look at sound intensity.
- The **sound intensity level**, $\beta$, is measured in decibels.
Sound Intensity Level

- To find the sound intensity level, \( \beta = 10 \log \frac{I}{I_0} \)
  - \( I_0 = 1.00 \times 10^{-12} \text{ W/m}^2 \)
- If \( I = I_0 \), then \( \beta = 0 \text{ dB} \)
  - This does not mean there is no sound
  - It does mean that the sound is at the same intensity as the lower limit of human hearing
- For every factor of 10 increase in intensity, the intensity level increases by 10 dB
- The intensity levels of some common sounds are listed in table 13.2
# Intensity Level of Some Sounds

## Table 13.2: Intensity Level of Some Common Sounds

<table>
<thead>
<tr>
<th>Sound</th>
<th>Intensity Level (dB)</th>
<th>Sound</th>
<th>Intensity Level (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold of pain for people</td>
<td>130</td>
<td>City traffic</td>
<td>70</td>
</tr>
<tr>
<td>Jet takeoff at a distance of 100 m</td>
<td>90–120</td>
<td>Normal conversation</td>
<td>60–70</td>
</tr>
<tr>
<td>Rock concert</td>
<td>110–120</td>
<td>Whisper</td>
<td>20</td>
</tr>
<tr>
<td>Thunder (nearby)</td>
<td>110</td>
<td>Pin dropping</td>
<td>10</td>
</tr>
<tr>
<td>Factory noise</td>
<td>80</td>
<td>Threshold of human hearing</td>
<td>0</td>
</tr>
</tbody>
</table>
Human Perception of Sound

- The lowest line plots the intensity of the minimum detectable sound as a function of the frequency.
- Doubling the perceived loudness corresponds to moving from one contour line to the next.
- The highest contour curve has a loudness at which the ear is damaged.
  - Occurs at $\beta \approx 120$ dB.
- The loudness contours depend on frequency.

Section 13.2
• Intensity is proportional to the square of the pressure amplitude
• There is a relationship between the threshold intensity for human hearing $I_o$ and the smallest pressure oscillation that can be detected by the ear
• A sound intensity of $I_o = 1.00 \times 10^{-12} \text{ W/m}^2$ corresponds to a pressure amplitude of $p_o = 2 \times 10^{-5} \text{ Pa}$
• This is about $2 \times 10^{-10}$ times smaller than atmospheric pressure
Standing Sound Waves – Closed Pipe

- Assume a sound wave traveling back and forth in a pipe closed at both ends
- The velocity and displacement will be zero at the ends of the pipe
- **Nodes** occur where there is zero displacement
- **Antinodes** are the largest displacements
- The pressure forms pressure antinodes at the ends of the tube

\[ \lambda = 2L \]

Fundamental frequency

\[ f_1 = \frac{v_{\text{sound}}}{2L} \]

Standing wave envelopes

\[ d_{\text{molecule}} = 0 \text{ at both ends} \]

(displacement nodes)

\[ v_{\text{molecule}} = 0 \text{ at both ends} \]

\[ p \]

Pressure node

Pressure antinodes

Standing wave on a string
Closed Pipe Harmonics

- Some other possible standing waves for displacement and pressure are shown.
- The frequencies of the standing waves are
  \[ f_n = \frac{n \frac{v_{\text{sound}}}{2L}} \] and
  \[ f_n = n f_1 \text{ with } n = 1, 2, 3, K \]
- \( f_1 \) is the fundamental frequency
- \( n \) is the harmonic number

\[ \lambda = L \]

Second harmonic: \( f = \frac{v_{\text{sound}}}{L} = 2f_1 \)

\[ \lambda = 2L/3 \]

Third harmonic: \( f = \frac{3v_{\text{sound}}}{2L} = 3f_1 \)
Standing Waves – Pipe Open at One End

- At the closed end, there will be a displacement node and a pressure antinode
- At the open end, there will be a pressure node and a displacement antinode

\[ \lambda = 4L \]

Fundamental frequency: \[ f_1 = \frac{v_{\text{sound}}}{4L} \]
Pipe Closed at One End – Harmonics

- Some other possible standing waves for displacement and pressure are shown.
- The frequencies of the standing waves are
  
  \[ f_n = n \frac{v_{\text{sound}}}{4L} \quad \text{and} \quad f_n = n f_1 \quad \text{with} \quad n = 1, 3, 5, \ldots \]

  - \( f_1 \) is the fundamental frequency and \( n \) is the harmonic number.
  - These harmonics are different than those in a pipe closed at both ends.

\[ \lambda = 4L/3 \quad \text{Third harmonic:} \quad f = \frac{3v_{\text{sound}}}{4L} = 3f_1 \]

\[ \lambda = 4L/5 \quad \text{Fifth harmonic:} \quad f = \frac{5v_{\text{sound}}}{4L} = 5f_1 \]
Standing Wave Summary

- The closed end of a pipe is a pressure antinode for the standing wave.
- The open end of a pipe is a pressure node for the standing wave.
- A pressure node is always a displacement antinode, and a pressure antinode is always a displacement node.
- These three points will allow you to predict the allowed frequencies of standing sound waves in pipes.
Harmonics Summary

- The patterns of standing wave frequencies are shown.
- The frequencies depend on whether the ends of the pipe are opened or closed.
Real Musical Tones

- Pipes are the basis for many musical instruments
- The standing wave in the instrument is a combination of standing waves with different frequencies
- These combination tones are often said to have a property called **timbre**
  - Also called tone color
- The timbre depends on the mix of frequencies
- The timbre is different for different instruments and how the instrument is played
Beat Frequency

- When two tones are played together, the superposition principle indicates the sound pressures will add.
- The amplitude of this combination pressure wave oscillates.
- These amplitude oscillations are called **beats**.
- The frequency of the oscillations is the **beat frequency**, $f_{\text{beat}}$.
  - $f_{\text{beat}} = | f_1 - f_2 |$
- Beats can be used to tune musical instruments.

Section 13.4
Reflection

- A sound wave with a plane front reflects from a flat surface
  - The reflection is mirror-like
- The angle of incidence equals the angle of reflection
- Mirror-like reflection will occur as long as the size of the reflecting surface is large compared to the wavelength of the sound
Scattering

- When an incoming plane wave strikes a small object, it does not undergo mirror-like reflection.
- At least some sound is “scattered” in all directions.
- This process is called scattering.

Scattering is important when $\lambda_{\text{sound}}$ is comparable to or larger than the size of the object.
Doppler Effect

- The phenomenon of the frequency heard by an observer being different that the frequency emitted by the source is called the *Doppler Effect*
  - Named for Christian Doppler, who discovered it
- Object moving toward the observer
  - The distance between wave crests decreases
  - The frequency measured by the observer is higher
- Object moving away from the observer
  - The distance between wave crests increases
  - The frequency measured by the observer is lower
Doppler Effect – Diagrams

**Section 13.6**
Doppler Effect – Equations

• For a source moving toward an observer:

\[ f_{\text{obs}} = \frac{f_{\text{source}}}{1 - \left( \frac{v_{\text{source}}}{v_{\text{sound}}} \right)} \]

• For a source moving away from an observer:

\[ f_{\text{obs}} = \frac{f_{\text{source}}}{1 + \left( \frac{v_{\text{source}}}{v_{\text{sound}}} \right)} \]

• The difference between the frequency heard by the observer and the source frequency is called the **Doppler Shift**
Doppler Effect – General

- The observer could also be moving and thus produce a Doppler shift

\[ f_{\text{obs}} = f_{\text{source}} \left[ \frac{1 \pm \left( \frac{v_{\text{obs}}}{v_{\text{sound}}} \right)}{1 \pm \left( \frac{v_{\text{source}}}{v_{\text{sound}}} \right)} \right] \]

- The + or – signs are chosen depending on whether the source and observer are moving toward or away from each other
- Frequency is increased when moving toward each other
- Frequency is decreased when moving away from each other

Section 13.6
A speed gun uses the Doppler effect with reflected electro-magnetic waves to measure the speed of a moving object.

As the initial waves hit the object, it acts like a moving observer.

For the scattered rays, the object acts like a moving source.

The speed gun uses the Doppler-shifted frequency to deduce the speed of the object.
Doppler Effect Example: Bats

- Bats employ an approach similar to the speed gun
- Bats generate pulses of ultrasonic waves
- These waves are reflected and the bat uses the reflected sound to judge its environment
Shock Waves

- The speed of the wave’s source can be greater than the speed of the wave.
- When the source moves at or faster than the speed of the wave, the pressure in front of the object piles up along a conic envelope.
- As many different sound waves arrive at a point on the envelope, they produce a very loud sound intensity and form a *shock wave*. 

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Section 13.6
Acoustic Thermometry

- Acoustic thermometry has been developed to study global warming.
- It uses the temperature dependence of the speed of sound to measure changes in the temperature of the oceans.
- The wave can travel long distances and by determining the travel time, its speed can be found.
  - Current precision for the time is about 20 ms.
- From the speed, the temperature of the water can be determined.
Ultrasound Images

- Ultrasonic imaging uses sound waves to obtain images inside a material
  - The most familiar use is to produce views inside the human body
- The depth of objects inside the body is determined by the time it takes the reflected ray to return to the detector
- Some medical ultrasounds also use the Doppler effect