Physics 161
Lecture 19
Sound waves

November 6, 2018
Lecture 19: learning objectives

Lecture 18 topics:
Transverse and Longitudinal Travelling Waves. Wavespeed, Wavelength, Frequency
Wave Interference, Reflection, Phase change.

This lecture 19

We will define the characteristics of sound waves and the speed of sound in air.

We will define sound intensity level, and the threshold of hearing and of pain. You will be able to discuss wave fronts and rays in spherical and plane waves.

We will describe standing waves and calculate harmonics of strings under tension and Sound in air columns.
iClicker question: frequency

When the frequency of a transverse wave on a string is doubled, what happens:

a) the wavelength doubles.
b) the propagation speed doubles.
c) the wavelength halves.
d) the propagation speed halves.
e) wavelength and speed stay the same.
Sound waves are **longitudinal** waves generated by vibrations in a medium, such as air or water.
Standing waves

**Sum of two waves:** Incident and reflected waves combine according to the superposition principle.

All points move along the y-axis with the same frequency, but different amplitudes.

The wave pattern is stationary along x-axis. Does not travel.

Only specific wavelength are allowed. Others do not ‘fit’.
Standing waves on string

Only allowed wavelength $\lambda_n$ for string of length $L$ fixed at both ends ($n = 1, 2, 3, \ldots$). Results in natural frequencies $f_n$.

\[ \lambda_n = \frac{2L}{n} \]

\[ f_n = \frac{n v}{2L} \]
iClicker question: standing waves

A certain string of 2.5 m with fixed ends allows standing waves with wavelength $\lambda_n$ and frequencies $f_n$ with $n = 1, 2, 3, \ldots$

If I change the tension in the string what happens:

a) The set of wavelength and frequencies will be the same.
b) Both the set of wavelength and frequencies will change.
c) The set of wavelength will change but the set of frequencies will be the same.
d) The set of wavelength will not change and the set of frequencies will change.
Standing waves in air columns

$\lambda_n = 2L/n$

$\lambda_1 = 2L$

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

First harmonic

$\lambda_2 = L$

$f_2 = \frac{v}{L} = 2f_1$

Second harmonic

$\lambda_3 = \frac{2}{3}L$

$f_3 = \frac{3v}{2L} = 3f_1$

Third harmonic

$\lambda_4 = \frac{4}{3}L$

$f_4 = \frac{3v}{4L} = 3f_1$

Fourth harmonic

$\lambda_5 = \frac{4}{5}L$

$f_5 = \frac{5v}{4L} = 5f_1$

Fifth harmonic

$\lambda_n = 4L/n$

$\lambda_1 = 4L$

$f_1 = \frac{v}{\lambda_1} = \frac{v}{4L}$

First harmonic

$\lambda_2 = 2L$

$f_2 = \frac{v}{L} = 2f_1$

Second harmonic

$\lambda_3 = \frac{4}{3}L$

$f_3 = \frac{3v}{4L} = 3f_1$

Third harmonic

$\lambda_4 = \frac{4}{5}L$

$f_4 = \frac{5v}{4L} = 5f_1$

Fourth harmonic

$\lambda_n = 2L/n$

$n = 1, 2, 3, \ldots$

$\lambda_n = 4L/n$

$n = 1, 3, 5, \ldots$
\[ \lambda_n = \frac{2L}{n} \]

\[ f_n = n \frac{v}{2L} \]

\( n = 1, 2, 3, \ldots \)
\[ \lambda_n = \frac{4L}{n} \]

\[ f_n = n \frac{v}{4L} \]

\( n = 1, 3, 5, \ldots \)
Problem: organ pipe

Two adjacent standing wave frequencies of an organ pipe are \(550\, \text{Hz}\) and \(650\, \text{Hz}\). \(V_{\text{sound}} = 343\, \text{m/s}\). What is the

a) fundamental frequency?
b) length of the pipe?
c) What kind of organ pipe?
There are three frequency ranges of sound waves.

**Audible:** (to humans)
Longitudinal waves that lie within the range of sensitivity of the human ear, approximately 20 to 20,000 Hz.

**Infrasonic:** (audible to elephants and whales)
Longitudinal waves with frequencies below the range of sensitivity of the human ear (below ~ 20 Hz).

**Ultrasonic:** (audible to bats)
Longitudinal waves with frequencies above the range of sensitivity of the human ear (above ~ 20,000 Hz).
Speed of sound

In general, the speed of sound is of the form:

\[ v = \sqrt{\frac{\text{elastic property}}{\text{inertial property}}} \]

In general for gas:

\[ v = \sqrt{\frac{B}{\rho}} \]

B is COMPRESSIBILITY
\[ \rho \] is GAS DENSITY

Recall transverse waves on a string:

\[ v = \sqrt{\frac{F_T}{\mu}} \]

\[ F_T \] is TENSION
\[ \mu \] is MASS DENSITY

Speed of sound in a gas depends on the temperature:

\[ v = v_0 \sqrt{\frac{T}{273 \text{ K}}} \]

\[ v_0 = 331 \text{ m/s for air} \]
iClicker question: water sounds

A sound wave of 343 Hz is incident on the surface of water and is transmitted from air into the water. What is the wavelength of the transmitted sound in water?

\[ V_{\text{sound in water}} = 1493 \text{ m/s} \]
\[ V_{\text{sound in air}} = 331 \text{ m/s} \]

a) 1 m.
b) about 5 m.
c) about 0.2 m.
d) 2 m.
e) 10 m.
iClicker question: glass

What will be the frequency of the new note, relative to the first note, when the glass is partially filled with water:

a) Higher.
b) Lower.
c) The same.
Wave harmonics in two dimensions

Nodes in wine glasses:

Not on exam.
Power and intensity

Power: \( P \)

The rate of energy flow (energy per unit time).

\[
P = \frac{\Delta E}{\Delta t}
\]

Power is measured in Watts (W) where 1 W = 1 J/s.

Intensity: \( I \)

The intensity of a wave is the rate of energy flow (Power \( P \)) through a surface per unit area.

\[
I = \frac{P}{A}
\]

Intensity is measured in units of \( \text{W/m}^2 \).

Example of area \( A \) is shown in next slide: Spherical area around a point source,
Spherical waves

An oscillating point source generates a spherical wave (in all directions).

Intensity of a spherical wave at distance $r$ from the source

$$I = \frac{P_{\text{ave}}}{4\pi r^2}$$

Relative intensity of two wave fronts for the same central point source.

$$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2}$$
Relative Intensity and decibels

Relative intensity (intensity level):
The intensity of a sound wave, relative to the intensity at the threshold of hearing, $I_0$.

$$\beta = 10 \log \left( \frac{I}{I_0} \right)$$

$I_0 = 1.0 \times 10^{-12} \text{ W/m}^2$

Relative intensity is measured in **decibels (dB)**.

Do not confuse relative intensity with intensity!

PAIN THRESHOLD AT 120 dB.

**Table 14.2** Intensity Levels in Decibels for Different Sources

<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>Subway, 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>
The intensity level of sound at a distance of 4 m away from a source is **40 dB**. What is the intensity level of sound at a distance of 1 m from the source?

a) 40 dB.
b) 160 dB.
c) 80 dB.
d) 52 dB.
e) 48 dB.

Note:
\[ \log 16 = 1.2 \]
\[ \log(a \times b) = \log(a) + \log(b) \]
\[ \log(a/b) = \log(a) - \log(b) \]
One of the loudest sounds in recent history was that made by the explosion of Krakatoa on August 26-27, 1883. According to barometric measurements, the sound had a decibel level of 180 dB at a distance of 161 km. What was the intensity level on Rodriguez Island, 4 800 km away?
The Doppler Effect

**Doppler effect:** The change in wave frequency arising from a moving source, observer or both.

The Doppler Effect occurs for all waves, but we will focus on the effect for sound waves.
We will consider:
1. Moving observer.
2. Moving source. (SIREN OF FIRE TRUCK)
3. The general case (both moving).
The Doppler Effect

Doppler effect: The change in wave frequency arising from a moving source, observer or both.

Moving source $S$, Observer at rest

$$f_O = f_S \left( \frac{v}{v - v_S} \right)$$

The source producing the water waves is moving to the right.
iClicker question: Doppler ball

What will be the frequency modulation that I perceive as I whirl the Doppler ball overhead?

a) In phase with the modulation with which you whirl.
b) I will not perceive any modulation.
Shock waves if \((v_s > v)\)

A source moving at \(v_s\), faster than the speed of sound \(v\), generates a shock wave.

The envelope of the wave fronts forms a cone with half-angle of \(\sin \theta = \frac{v}{v_s}\).

The large pressure variation in the shock wave condenses water vapor into droplets.
Demo: boundary conditions

$\lambda_1 = 2L \quad f_1 = \frac{v}{2L}$

$\lambda_2 = L \quad f_2 = \frac{v}{L}$

$\lambda_3 = \frac{2L}{3} \quad f_3 = \frac{3v}{2L}$

$\lambda_4 = \frac{L}{2} \quad f_4 = \frac{2v}{L}$

$\lambda_5 = \frac{2L}{5} \quad f_5 = \frac{5v}{2L}$
3 dimensional wave

Animation