

Phy 212: General Physics II

Chapter 17: Waves II Lecture Notes

Sound



1. A longitudinal traveling wave
2. Produced by vibrations in a medium
 - a. The disturbance is the local change in pressure generated by the vibrating object
 - b. It travels because of the molecular interactions.
3. The region of increased pressure (compared to the undisturbed pressure) is called **condensation**
4. The region of lower pressure is called **rarefaction**.
5. The maximum increase in pressure (ΔP_m) is the **amplitude of the pressure wave**. (measurable)
6. **Frequency of “perceivable” sound: 20Hz to 20000Hz.**
 - a. Pressure waves below 20 Hz are called infrasonic waves
 - b. Pressure waves over 20,000Hz are called ultrasonic waves.

Description of Sound Waves

1. The propagation of sound waves occurs due to the oscillations of individual particles with the medium producing traveling waves of pressure fluctuations
2. The general form of particle oscillation:

$$s(x,t) = s_m \cos(kx - \omega t)$$

where s_m is the magnitude of the particle displacement

3. The general equation for the pressure fluctuations:

$$\Delta P(x,t) = \Delta P_m \sin(kx - \omega t)$$

4. The pressure fluctuation magnitude is given by:

$$\Delta P_m = (\rho v_{\text{wave}} \omega) s_m$$

The Speed of Sound

1. **Speed of sound** (v_{sound}) in a medium depends on the compressive properties of the medium.
2. Due to the high frequencies, the compressions & expansions are fast and no heat is exchanged (*adiabatic*).
3. Sound waves can travel in gases, liquids and solids.

4. The speed of sound in gases:

$\gamma = 7/5$ (for diatomic gases)

$k = 1.38 \times 10^{-23}$ J/K (Boltzmann's Constant)

m_{gas} = avg mass of gas particle ($m_{\text{air}} = 4.74 \times 10^{-26}$ kg)

$$v_{\text{in gas}} = \sqrt{\frac{B_{\text{gas}}}{\rho_{\text{gas}}}} \quad \text{or} \quad \sqrt{\frac{\gamma k T}{m_{\text{gas}}}}$$

5. The speed of sound in liquids:

B_{liquid} is the adiabatic bulk modulus

ρ_{liquid} is the liquid density

$$v_{\text{in liquid}} = \sqrt{\frac{B_{\text{liquid}}}{\rho_{\text{liquid}}}}$$

6. The speed of sound in solids:

Y_{solid} is the Young's modulus

ρ_{solid} is the solid density

$$v_{\text{in solid}} = \sqrt{\frac{Y_{\text{solid}}}{\rho_{\text{solid}}}}$$

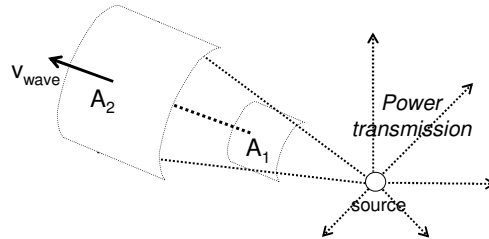
Sound Intensity

- **Waves transport energy without transporting mass.** The amount of energy transported per second is the **power** (P) of the wave (in W)
- **Intensity** is a measure of power transmitted by a wave per unit area:

$$I = \frac{\text{Power}}{\text{Area}} = \frac{P}{A} = \rho_{\text{medium}} v_{\text{wave}} \omega^2 s_m^2$$

- The energy transmission (power) of the sound wave is determined by the source. The power is distributed (spreads) in all directions. Far away from the source, the power is spread over a greater area.
- For a point source, intensity decreases inversely with the square of the distance from the source:

$$I(r) = \frac{P}{A} = \frac{P}{4\pi r^2}$$



Loudness & Decibels

1. The human does not perceive sound intensity linearly but rather logarithmically

$$\text{Perceived Loudness: } I_{\text{perceived}} \propto \log(I_{\text{actual}})$$

2. The average minimum perceivable sound intensity:

$$I_0 \sim 1 \times 10^{-12} \text{ W/m}^2$$

3. The decibel scale was been developed to “linearize” the sound intensity to the human ear perception (β):

$$\beta = (10 \text{ dB}) \cdot \log\left(\frac{I}{I_0}\right) \quad \left\{ \text{where } I_0 = 10^{-12} \frac{\text{W}}{\text{m}^2} \right\}$$

or

$$\beta = (10 \text{ dB}) \cdot [\log(I) + 12]$$

Comparison of 10W & 100W Sound Sources

Consider 2 “point sound sources” with power outputs of 10 W and 100 W, respectively.

1. The ratio of sound intensity at 1 m is:

$$\frac{I_{100W}}{I_{10W}} = \frac{\left(\frac{100W}{4\pi(1m)^2} \right)}{\left(\frac{10W}{4\pi(1m)^2} \right)} = \frac{\left(7.96 \frac{W}{m^2} \right)}{\left(0.796 \frac{W}{m^2} \right)} = 10$$

2. The ratio of decibel levels at 1m is:

$$\begin{aligned} \frac{\beta_{100W}}{\beta_{10W}} &= \frac{(10 \text{ dB}) \cdot \log\left(\frac{I_{100W}}{I_o}\right)}{(10 \text{ dB}) \cdot \log\left(\frac{I_{10W}}{I_o}\right)} = \frac{(10 \text{ dB})[\log(I_{100W}) - \log(I_o)]}{(10 \text{ dB})[\log(I_{10W}) - \log(I_o)]} \\ &= \frac{(10 \text{ dB})(\log(7.96) + 12)}{(10 \text{ dB})(\log(0.796) + 12)} = \frac{129 \text{ dB}}{119 \text{ dB}} = 1.08 \end{aligned}$$

Sound Interference & Beats

1. When 2 sound waves the resultant wave pattern exhibits both constructive and destructive interference ([link](#))
2. When the amplitudes of the 2 waves are similar but the frequencies are slightly different then:
 - a. The frequency of the resultant wave is roughly the average frequency of the 2 waves
 - b. The combined effect of interference produces periodic rises and drops in loudness called beats
 - c. The frequency of the beats (f_{beat}) is equal to the difference between the 2 sound frequencies:

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

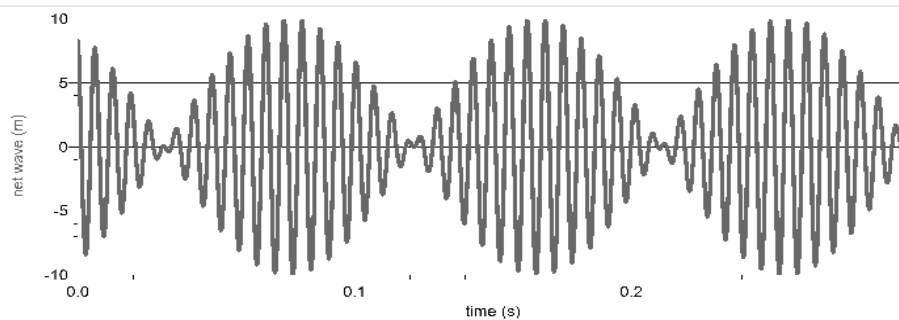
3. Musicians often tune their musical instruments by listening to beat frequency ([link](#))

Beats

The superposition of 2 sound waves:

$$f_{\text{wave1}} = 159.2 \text{ Hz}$$

$$f_{\text{wave2}} = 148.0 \text{ Hz}$$



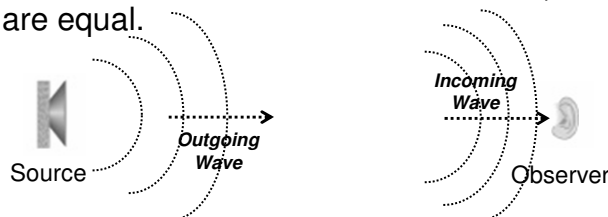
The resulting waveform exhibits a beat frequency of:

$$f_{\text{beat}} = f_{\text{wave1}} - f_{\text{wave2}} = 159.2 \text{ Hz} - 148.0 \text{ Hz} = 11.2 \text{ Hz}$$

Doppler Effect

Physical Argument:

- The frequency of the source producing the wave equals the number of cycles per second.
- The frequency measured by an observer is the number of crests (condensations) encountered per second.
- When both the source and the observer are at rest, the 2 frequencies are equal.



- When one or both are in motion, the source and observed frequencies are different.
- The difference between source and observed frequency is called **Doppler shift**

Doppler Shift

(Moving source, observer at rest)

The apparent wavelength is changed because of the relative motion of source and observer

Source moving toward observer

$$f_{\text{observer}} = f_s \left(\frac{1}{1 - \frac{v_s}{v_{\text{wave}}}} \right)$$

Notes:

v_s = speed of source

v_{wave} = speed of sound

f_s = frequency of source

Source moving away from the observer

$$f_{\text{observer}} = f_s \left(\frac{1}{1 + \frac{v_s}{v_{\text{wave}}}} \right)$$

Doppler Shift

(Moving observer, source at rest)

The time between encountering 2 crests changes for the observer resulting in an altered perceived frequency (wave speed is observed to be altered!)

Observer moving toward source

$$f_{\text{observer}} = f_s \left(1 + \frac{v_o}{v_{\text{wave}}} \right)$$

Notes:

v_o = speed of observer

v_{wave} = speed of sound

f_s = frequency of source

Observer moving away from source

$$f_{\text{observer}} = f_s \left(1 - \frac{v_o}{v_{\text{wave}}} \right)$$

The Doppler Shift (General Form)

The equations for both moving source and moving observer can be combined to yield the general equation for Doppler Shift:

$$f_{\text{observer}} = f_s \left(\frac{1 \pm \frac{v_o}{v_{\text{wave}}}}{1 \pm \frac{v_s}{v_{\text{wave}}}} \right)$$

Doppler Effect Application: The “radar” gun

The doppler “radar” gun uses radio frequency light waves to measure vehicle speed ($f_{\text{gun}} = 24.2 \times 10^9 \text{ Hz}$ & $v_{\text{wave}} = 3.0 \times 10^8 \text{ m/s}$).

An emitted light wave undergoes a doppler shift as it reaches a moving vehicle (moving observer). The reflected wave then undergoes a 2nd doppler shift as it returns to the radar gun (moving source).

Analysis:

As the wave reaches the moving vehicle the shifted incident wave is:

$$f_{\text{reflected}} = f_{\text{gun}} \left(1 + \frac{v_{\text{car}}}{v_{\text{wave}}} \right)$$

The reflected wave is also shifted and observed wave as measured by the detector is:

$$f_{\text{received}} = \frac{f_{\text{reflected}}}{1 - \frac{v_{\text{car}}}{v_{\text{wave}}}} = f_{\text{gun}} \left(\frac{1 + \frac{v_{\text{car}}}{v_{\text{wave}}}}{1 - \frac{v_{\text{car}}}{v_{\text{wave}}}} \right)$$

The measured speed of the vehicle is:

$$v_{\text{car}} \approx v_{\text{wave}} \left(\frac{\Delta f}{2f_{\text{gun}}} \right)$$