Analytical Physics 1B Lecture 7:
Sound

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**Sound Waves**

- **Longitudinal** waves in a medium (air, solids, liquids, etc.)
  - Human ear is sensitive to frequencies between 20 and 20,000 Hz
- Think about sound as a **variation of pressure** as a function of position and time

![Diagram of sound waves and particle displacement](image)
Sound Intensity

- Intensity is like “loudness”
  - However, loudness is perceptual and depends on the frequency
  - Intensity is the power (power=energy per unit time) per unit area
- Intensity decreases with distance
  - proportional to $1/r^2$ (like gravity)

At distance $r_1$ from the source, the intensity is $I_1$.
At a greater distance $r_2 > r_1$, the intensity $I_2$ is less than $I_1$: the same power is spread over a greater area.
# Sound Intensity

- Measured in decibels

\[ \beta = (10 \text{ dB}) \log \frac{I}{I_0} \quad I_0 = 10^{-12} \text{ W/m}^2 \]

<table>
<thead>
<tr>
<th>Source or Description of Sound</th>
<th>Sound Intensity Level, $\beta$ (dB)</th>
<th>Intensity, $I$ (W/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Military jet aircraft 30 m away</td>
<td>140</td>
<td>$10^2$</td>
</tr>
<tr>
<td>Threshold of pain</td>
<td>120</td>
<td>1</td>
</tr>
<tr>
<td>Riveter</td>
<td>95</td>
<td>$3.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>Elevated train</td>
<td>90</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Busy street traffic</td>
<td>70</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Ordinary conversation</td>
<td>65</td>
<td>$3.2 \times 10^{-6}$</td>
</tr>
<tr>
<td>Quiet automobile</td>
<td>50</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Quiet radio in home</td>
<td>40</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>Average whisper</td>
<td>20</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>Rustle of leaves</td>
<td>10</td>
<td>$10^{-11}$</td>
</tr>
<tr>
<td>Threshold of hearing at 1000 Hz</td>
<td>0</td>
<td>$10^{-12}$</td>
</tr>
</tbody>
</table>
Open and Closed Pipes

- Characteristic frequencies of a pipe depend on its length and whether it is open or closed
  - (As well as the speed of sound in air)

(a) Fundamental: $f_1 = \frac{v}{4L}$

(b) Third harmonic: $f_3 = 3 \frac{v}{4L} = 3f_1$

(c) Fifth harmonic: $f_5 = 5 \frac{v}{4L} = 5f_1$

Closed end is always a displacement node.

(a) Fundamental: $f_1 = \frac{v}{2L}$

(b) Second harmonic: $f_2 = 2 \frac{v}{2L} = 2f_1$

(c) Third harmonic: $f_3 = 3 \frac{v}{2L} = 3f_1$

Open end is always a displacement antinode.
**INTERFERENCE**

• Sounds waves interfere in the same way that mechanical waves interfere

  ![Diagram of interference patterns](image)

• Suppose you have two identical waves being transmitted by two different speakers
  
  • **Constructive** interference occurs when the distance travelled by the two differs by an **integer** # of wavelengths 0, λ, 2λ, 3λ, …
  
  • **Destructive** interference occurs when the distance travelled by the two differs by a **half-integer** # of wavelengths λ/2, 3λ/2, 5λ/2, …
**Beats**

- If two sound waves are played with the same amplitude and nearly the same frequency, you hear a “beat”

\[
f_{\text{beat}} = f_a - f_b
\]

Two sound waves with slightly different frequencies

(a) Waves in phase with each other

(b) Waves out of phase with each other

The two waves interfere constructively when they are in phase and destructively when they are a half-cycle out of phase. The resultant wave rises and falls in intensity, forming beats.
Doppler Effect

- Consider the case when an observer is moving towards a stationary source.
  - The frequency of the listener is
    
    \[ f_L = \frac{v + v_L}{\lambda} = \left(1 + \frac{v_L}{v}\right) f_S \]

  - Velocity of listener (L) = \( v_L \)
  - Velocity of source (S) = 0 (at rest)
  - Speed of sound wave = \( v \)
  - Positive direction: from listener to source
**Doppler Effect**

- When the **source** is moving, the situation is more complicated
  - The wavelengths **behind** the direction of motion are stretched out
  - The wavelengths **in front of** the direction of motion are compressed

- Velocity of listener (L) = $v_l$
- Velocity of source (S) = $v_s$
- Speed of sound wave = $v$
- Positive direction: from listener to source
**Doppler Effect**

- The wavelength **in front of** the source is

\[ \lambda_{\text{front}} = \frac{v}{f_S} - \frac{v_s}{f_S} \]

- The wavelength **behind** the source is

\[ \lambda_{\text{behind}} = \frac{v}{f_S} + \frac{v_s}{f_S} \]

- Velocity of listener \((L) = v_L\)
- Velocity of source \((S) = v_s\)
- Speed of sound wave \(= v\)
- Positive direction: from listener to source
DOPPLER EFFECT

• The frequency heard by the listener is

$$f_L = \frac{v + v_L}{\lambda_{\text{behind}}} = \frac{v + v_L}{v + v_S} f_S$$

• Note that the velocities are **signed** (that is there is an implied direction)
A MECHANICAL WAVE

• https://www.youtube.com/watch?v=TKF6nFzpHBU