Phys101 Lectures 32, 33
Sound, Decibels, Doppler Effect

Key points:

• Intensity of Sound: Decibels
• Doppler Effect

Ref: 12-1,2,7.
Sound can travel through any kind of matter, but not through a vacuum.

The speed of sound is different in different materials; in general, it is slowest in gases, faster in liquids, and fastest in solids.

The speed depends somewhat on temperature, especially for gases.

**Characteristics of Sound**

**TABLE 12–1 Speed of Sound in Various Materials (20°C and 1 atm)**

<table>
<thead>
<tr>
<th>Material</th>
<th>Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>343</td>
</tr>
<tr>
<td>Air (0°C)</td>
<td>331</td>
</tr>
<tr>
<td>Helium</td>
<td>1005</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>1300</td>
</tr>
<tr>
<td>Water</td>
<td>1440</td>
</tr>
<tr>
<td>Sea water</td>
<td>1560</td>
</tr>
<tr>
<td>Iron and steel</td>
<td>≈ 5000</td>
</tr>
<tr>
<td>Glass</td>
<td>≈ 4500</td>
</tr>
<tr>
<td>Aluminum</td>
<td>≈ 5100</td>
</tr>
<tr>
<td>Hardwood</td>
<td>≈ 4000</td>
</tr>
<tr>
<td>Concrete</td>
<td>≈ 3000</td>
</tr>
</tbody>
</table>
Characteristics of Sound

Loudness: related to intensity of the sound wave

Pitch: related to frequency

Audible range: about 20 Hz to 20,000 Hz; upper limit decreases with age

Ultrasound: above 20,000 Hz;

Infrasound: below 20 Hz
The intensity of a wave is the energy transported per unit time across a unit area.

The human ear can detect sounds with an intensity as low as $10^{-12}$ W/m$^2$ and as high as 1 W/m$^2$.

Perceived loudness, however, is not proportional to the intensity.

**TABLE 12–2 Intensity of Various Sounds**

<table>
<thead>
<tr>
<th>Source of the Sound</th>
<th>Sound Level (dB)</th>
<th>Intensity (W/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet plane at 30 m</td>
<td>140</td>
<td>100</td>
</tr>
<tr>
<td>Threshold of pain</td>
<td>120</td>
<td>1</td>
</tr>
<tr>
<td>Loud rock concert</td>
<td>120</td>
<td>1</td>
</tr>
<tr>
<td>Siren at 30 m</td>
<td>100</td>
<td>$1 \times 10^{-2}$</td>
</tr>
<tr>
<td>Auto interior, at 90 km/h</td>
<td>75</td>
<td>$3 \times 10^{-5}$</td>
</tr>
<tr>
<td>Busy street traffic</td>
<td>70</td>
<td>$1 \times 10^{-5}$</td>
</tr>
<tr>
<td>Talk, at 50 cm</td>
<td>65</td>
<td>$3 \times 10^{-6}$</td>
</tr>
<tr>
<td>Quiet radio</td>
<td>40</td>
<td>$1 \times 10^{-8}$</td>
</tr>
<tr>
<td>Whisper</td>
<td>20</td>
<td>$1 \times 10^{-10}$</td>
</tr>
<tr>
<td>Rustle of leaves</td>
<td>10</td>
<td>$1 \times 10^{-11}$</td>
</tr>
<tr>
<td>Threshold of hearing</td>
<td>0</td>
<td>$1 \times 10^{-12}$</td>
</tr>
</tbody>
</table>
Sound Level: Decibels

The loudness of a sound is much more closely related to the logarithm of the intensity.

Sound level is measured in **decibels (dB)** and is defined as:

\[
\beta \text{ (in dB)} = 10 \log \frac{I}{I_0}.
\]

\(I_0\) is taken to be the **threshold of hearing**:

\[
I_0 = 1.0 \times 10^{-12} \text{ W/m}^2.
\]
Example: Sound intensity on the street.

At a busy street corner, the sound level is 75 dB. What is the intensity of sound there?
Example: Loudspeaker response.

A high-quality loudspeaker is advertised to reproduce, at full volume, frequencies from 30 Hz to 18,000 Hz with uniform sound level ± 3 dB. That is, over this frequency range, the sound level output does not vary by more than 3 dB for a given input level. By what factor does the intensity change for the maximum change of 3 dB in output sound level?
Conceptual Example: Trumpet players.

A trumpeter plays at a sound level of 75 dB. Three equally loud trumpet players join in. What is the new sound level?
Example: Airplane roar.

The sound level measured 30 m from a jet plane is 140 dB. What is the sound level at 300 m? (Ignore reflections from the ground.)
Example: How tiny the displacement is.

Calculate the displacement of air molecules for a sound having a frequency of 1000 Hz at the threshold of hearing.
The ear’s sensitivity varies with frequency. These curves translate the intensity into sound level at different frequencies.
Doppler Effect

The Doppler effect occurs when a source of sound is moving with respect to an observer.

A source moving toward an observer appears to have a higher frequency and shorter wavelength; a source moving away from an observer appears to have a lower frequency and longer wavelength.
If we can figure out what the change in the wavelength is, we also know the change in the frequency.

When the source is approaching, the observed wavelength is shorter:

\[ \lambda' = \lambda - v_{source} T \]

Then the observed frequency is:

\[ f' = \frac{v}{\lambda'} = \frac{v}{\lambda - v_{source} T} \]

\[ = \frac{v}{\lambda \left(1 - \frac{v_{source} T}{\lambda}\right)} = \frac{f}{1 - \frac{v_{source} T}{\lambda}} \]

\[ = \frac{f}{1 - \frac{v_{source}}{v}} > f \]

\(v\) – velocity of sound
Doppler Effect

The change in the frequency is given by:

\[ f' = \frac{f}{\left(1 - \frac{v_{\text{source}}}{v_{\text{snd}}}\right)}. \]

Source approaching: Higher freq. \( f' > f \)

Similarly, if the source is moving away from the observer:

\[ f' = \frac{f}{\left(1 + \frac{v_{\text{source}}}{v_{\text{snd}}}\right)}. \]

Source receding: Lower freq. \( f' < f \)
If the observer is moving with respect to the source, things are a bit different. The wavelength remains the same, but the wave speed is different for the observer.

\[ v' = v + v_{obs} \]  
when the observer is approaching
For an observer moving toward a stationary source:

Observed sound velocity: \( v' = v + v_{obs} \)

Observed frequency:

\[
f' = \frac{v'}{\lambda} = \frac{v + v_{obs}}{\lambda} = \frac{v}{\lambda} \left(1 + \frac{v_{obs}}{v}\right) = f \left(1 + \frac{v_{obs}}{v}\right)
\]

Observer approaching: Higher freq.
\( f' > f \)

And if the observer is moving away:

\[
v' = v - v_{obs}
\]

\[
f' = \frac{v'}{\lambda} = \frac{v - v_{obs}}{\lambda} = \frac{v}{\lambda} \left(1 - \frac{v_{obs}}{v}\right) = f \left(1 - \frac{v_{obs}}{v}\right)
\]

Observer receding: Lower freq.
\( f' < f \)
Example: A moving siren.

The siren of a police car at rest emits at a predominant frequency of 1600 Hz. What frequency will you hear if you are at rest and the police car moves at 25.0 m/s (a) toward you, and (b) away from you?
Example: Two Doppler shifts.

A 5000-Hz sound wave is emitted by a stationary source. This sound wave reflects from an object moving toward the source. What is the frequency of the wave reflected by the moving object as detected by a detector at rest near the source?
Doppler Effect

All four equations for the Doppler effect can be combined into one; you just have to keep track of the signs!

\[ f' = f \left( \frac{v_{\text{snd}} \pm v_{\text{obs}}}{v_{\text{snd}} \mp v_{\text{source}}} \right). \]

The signs:

**Approaching:** higher freq. \( f' > f \)

**Receding:** lower freq. \( f' < f \)