Chapter 12

Sound
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12-1 Characteristics of Sound

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.

<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>
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; see ultrasonic camera focusing below

Infrasound: below 20 Hz
The intensity of sound is measured in decibels (dB). The human ear can detect sounds with an intensity as low as $10^{-12} \text{ W/m}^2$ 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>Busy street traffic</td>
<td>80</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>Noisy restaurant</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>30</td>
<td>$1 \times 10^{-9}$</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>
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:

\[ \beta \text{ (in dB)} = 10 \log \frac{I}{I_0}, \quad (12-1) \]

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

\[ I_0 = 1.0 \times 10^{-12} \text{ W/m}^2 \]
12-2 Intensity of Sound: Decibels

An increase in sound level of 3 dB, which is a doubling in intensity, is a very small change in loudness.

In open areas, the intensity of sound diminishes with distance:

$$I \propto \frac{1}{r^2}$$

However, in enclosed spaces this is complicated by reflections, and if sound travels through air the higher frequencies get preferentially absorbed.
Outer ear: sound waves travel down the ear canal to the eardrum, which vibrates in response

Middle ear: hammer, anvil, and stirrup transfer vibrations to inner ear

Inner ear: cochlea transforms vibrational energy to electrical energy and sends signals to the brain
The ear’s sensitivity varies with frequency. These curves translate the intensity into sound level at different frequencies.
Musical instruments produce sounds in various ways—vibrating strings, vibrating membranes, vibrating metal or wood shapes, vibrating air columns.

The vibration may be started by plucking, striking, bowing, or blowing. The vibrations are transmitted to the air and then to our ears.
12-4 Sources of Sound: Vibrating Strings and Air Columns

The strings on a guitar can be effectively shortened by fingering, raising the fundamental pitch.

The pitch of a string of a given length can also be altered by using a string of different density.
A piano uses both methods to cover its more than seven-octave range—the lower strings (at left) are both much longer and much thicker than the higher ones.
Wind instruments create sound through standing waves in a column of air.
A tube open at both ends (most wind instruments) has pressure nodes, and therefore displacement antinodes, at the ends.
12-4 Sources of Sound: Vibrating Strings and Air Columns

A tube closed at one end (some organ pipes) has a displacement node (and pressure antinode) at the closed end.
So why does a trumpet sound different from a flute? The answer lies in overtones—which ones are present, and how strong they are, makes a big difference.

The plot below shows frequency spectra for a clarinet, a piano, and a violin. The differences in overtone strength are apparent.
Sound waves interfere in the same way that other waves do in space.
Waves can also interfere in time, causing a phenomenon called beats. Beats are the slow “envelope” around two waves that are relatively close in frequency.
The Doppler effect occurs when a source of sound is moving with respect to an observer.

(a) At rest

(b) Fire truck moving
12-7 Doppler Effect

As can be seen in the previous image, a source moving toward an observer has a higher frequency and shorter wavelength; the opposite is true when a source is moving away from an observer.
If we can figure out what the change in the wavelength is, we also know the change in the frequency.

\[ d_{\text{source}} = v_{\text{source}} T \]

(b) Source moving

12-7 Doppler Effect
The change in the wavelength is given by:

\[ \lambda' = d - d_{\text{source}} \]

\[ = \lambda - v_{\text{source}} \frac{\lambda}{v_{\text{snd}}} \]

\[ = \lambda \left( 1 - \frac{v_{\text{source}}}{v_{\text{snd}}} \right). \]
12-7 Doppler Effect

And the change in the frequency:

\[ f' = \frac{f}{\left(1 - \frac{v_{\text{source}}}{v_{\text{snd}}}\right)} \]  
(source moving toward stationary observer) \hfill (12-2a)

If the source is moving away from the observer:

\[ f' = \frac{f}{\left(1 + \frac{v_{\text{source}}}{v_{\text{snd}}}\right)} \]  
(source moving away from stationary observer) \hfill (12-2b)
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.
12-7 Doppler Effect

We find, for an observer moving towards a stationary source:

\[ f' = \frac{(v_{snd} + v_{obs})}{v_{snd}} f, \]

or

\[ f' = \left(1 + \frac{v_{obs}}{v_{snd}}\right)f. \]  \hspace{2cm} \text{[observer moving toward stationary source] (12-3a)}

And if it is moving away:

\[ f' = \left(1 - \frac{v_{obs}}{v_{snd}}\right)f. \]  \hspace{2cm} \text{[observer moving away from stationary source] (12-3b)}
12-8 Shock Waves and the Sonic Boom

If a source is moving faster than the wave speed in a medium, waves cannot keep up and a shock wave is formed.

The angle of the cone is:

\[
\sin \theta = \frac{v_{\text{snd}}}{v_{\text{obj}}}, \quad (12-5)
\]
Shock waves are analogous to the bow waves produced by a boat going faster than the wave speed in water.
Aircraft exceeding the speed of sound in air will produce two sonic booms, one from the front and one from the tail.
Sonar is used to locate objects underwater by measuring the time it takes a sound pulse to reflect back to the receiver.

Similar techniques can be used to learn about the internal structure of the Earth.

Sonar usually uses ultrasound waves, as the shorter wavelengths are less likely to be diffracted by obstacles.
Ultrasound is also used for medical imaging. Repeated traces are made as the transducer is moved, and a complete picture is built.
Modern high-resolution ultrasound can produce very detailed images.
Summary of Chapter 12

• Sound is a longitudinal wave in a medium.
• The pitch of the sound depends on the frequency.
• The loudness of the sound depends on the intensity and also on the sensitivity of the ear.
• The strings on stringed instruments produce a fundamental tone whose wavelength is twice the length of the string; there are also various harmonics present.
Summary of Chapter 12

- Wind instruments have a vibrating column of air when played. If the tube is open, the fundamental is twice its length; if it is closed the fundamental is four times the tube length.

- Sound waves exhibit interference; if two sounds are at slightly different frequencies they produce beats.

- The Doppler effect is the shift in frequency of a sound due to motion of the source or the observer.