14: Waves and Sound

Types of waves (demo's)

**Transverse Waves**: “disturbance” is perpendicular to wave velocity, such as for waves on a string. (disturbance is a shear stress, only occurs in solids!)

**Longitudinal Waves**: “disturbance” is parallel to wave velocity, such as the compression waves on the slinky.

Water surface waves: mixture of longitudinal and transverse
Periodic Waves
a.k.a. Harmonic Waves, Sine Waves ...

Important characteristics of periodic waves

wave speed $v$: the speed of the wave, which depends upon the medium only.

wavelength $\lambda$: (greek lambda) the distance over which the wave repeats, it is also the distance between crests or troughs.

frequency $f$: the number of waves which pass a given point per second. The period of the wave is related to the frequency by $T = 1/f$.

Wavelength, speed and frequency are related by:

$$v \ T = \lambda \quad so \quad v = \lambda f$$

Amplitude $A$: the maximum displacement from equilibrium. The amplitude does not affect the wave speed, frequency, wavelength, etc.

$A$

$\Rightarrow$ Elastic Potential Energy and Kinetic Energy associated with wave depend upon Amplitude.

Energy per time (power) carried by a wave is proportional to the square of the amplitude.

“Loudness” depends upon amplitude.
Waves on a string

speed of pulse = wave speed = \( v \)

depends upon tension \( F \) and inertia (mass per length \( \mu \))

\[
v = \sqrt{\frac{F}{\mu}} = \sqrt{\frac{F}{m/L}}
\]
A 12 m rope is pulled tight with tension of 92 N. When one end is given a jerk, it takes 0.45 s for the disturbance to propagate to the other end. What is the mass of the rope?
Sound Waves:
  compression waves (longitudinal)
  sound waves in air travel at 343 m/s (20°C, 1 atm) = 770 mi/h
  sound waves in materials depends upon density (inertia) and compressibility (springiness)

Example: How far away was a lightning strike if the thunder is heard 5 s after the flash is seen?

<table>
<thead>
<tr>
<th>material</th>
<th>speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>aluminum</td>
<td>6420</td>
</tr>
<tr>
<td>granite</td>
<td>6000</td>
</tr>
<tr>
<td>steel</td>
<td>5960</td>
</tr>
<tr>
<td>pyrex</td>
<td>5640</td>
</tr>
<tr>
<td>copper</td>
<td>5010</td>
</tr>
<tr>
<td>fresh water (20°C)</td>
<td>1482</td>
</tr>
<tr>
<td>fresh water (0°C)</td>
<td>1402</td>
</tr>
<tr>
<td>hydrogen (0°C)</td>
<td>1284</td>
</tr>
<tr>
<td>helium (0°C)</td>
<td>965</td>
</tr>
<tr>
<td>air (20°C)</td>
<td>343</td>
</tr>
<tr>
<td>air (0°C)</td>
<td>331</td>
</tr>
</tbody>
</table>
More on sound waves:

Intensity

\[ I = \frac{P}{A} \]  (intensity is power per area)

decreases with square of distance (for spherical waves)

for a point source in 3-D

\[ I = \frac{P}{4\pi r^2} \]

Human hearing:

frequency \leftrightarrow pitch

human hearing is not uniform, most sensitive from 2000-5000 Hz

frequencies from 20Hz to 20,000 Hz

subsonic: frequencies below 20 Hz

ultra sonic: frequencies above 20,000 Hz

Intensity \leftrightarrow Loudness

Standard Scale: Intensity Level  \[ \beta = 10 \log \left( \frac{I}{I_0} \right) \]

decibels (dB), a logarithmic scale

\[ I_0 = 1E-12 \text{ W/m}^2 \] , “Barely audible”

20 dB increase in L means 100x in intensity, 3dB change means 2x

0 dB is barely audible, not 0 Intensity!

Pain at about 130 dB
Example: At a baseball game, a fan hears the crack of a bat at an intensity of 3.8E-7 W/m² at a distance of 140 m from the batter. What intensity is heard by the first base umpire, who is 27.4 m from the batter? What is the sound intensity level heard by the fan? What is the sound intensity level heard by the first base umpire?
Doppler Effect

Motion of source or detector can affect measured frequency

Stationary Source, Observer

Moving Source, Stationary Observer

\[ f' = \frac{f}{(1 \mp v_s/v)} \quad \text{moving source} \]

Stationary Source, Moving Observer

\[ f' = f \cdot (1 \pm v_o/v) \quad \text{moving observer} \]

Combined

\[ f' = \frac{f}{(1 \mp u_s/v)} \quad \text{moving source} \]
Example: A car moving at 18 m/s sounds its 550 Hz horn as it approaches a bicyclist. The bicyclist rides at 7.2 m/s towards the car. What frequency is heard by the bicyclist?
Reflections at a boundary
fixed end = “hard” boundary
Pulse is **inverted**

Reflections at a boundary
free end = “soft” boundary
Pulse is **not inverted**
Reflections at an interface

- light string to heavy string = “hard” boundary
  faster medium to slower medium

- heavy string to light string = “soft” boundary
  slower medium to faster medium

**Principle of Superposition: When Waves Collide!**

When pulses pass the same point,
add the two displacements
Standing Waves

vibrations in fixed patterns
effectively produced by the superposition of two traveling waves

\[ y = y_0 \sin\left(\frac{x}{\lambda} \pm \frac{t}{T}\right) \]

constructive interference: waves add
destructive interference: waves cancel

\[ \lambda = 2L \]

\[ 2\lambda = 2L \]  
\[ 3\lambda = 2L \]  
\[ 4\lambda = 2L \]
characteristic wavelengths

\[ \lambda = \frac{2L}{n} \quad n = 1, 2, 3, \ldots \]

longest wavelength \(\leftrightarrow\) lowest frequency

= fundamental frequency

\[ f_1 = \frac{v}{\lambda} = \frac{v}{2L} \]

harmonics

\[ f_n = \frac{v}{\lambda_n} = n \frac{v}{2L} = nf_1 \]

**Resonance**

When a system is subjected to a periodic force with a frequency equal to one of its natural frequencies, energy is rapidly transferred to the system.

events:
- musical instruments with fundamental or overtones
- mechanical vibrations
Example: What is the wave speed of a guitar string whose fundamental frequency is 330 Hz if the length of string free to vibrate is 0.651 m? What is the tension in the string if the string’s linear mass density is 0.441 g/m³?
Standing Waves II pipe open at one end

\[ \lambda = 4L \]

\[ 3\lambda = 4L \]

\[ 5\lambda = 4L \]

\[ 7\lambda = 4L \]

\[ \lambda = \frac{4L}{n}; \quad n = 1, 3, 5\ldots \]

\[ f_1 = \frac{v}{\lambda} = \frac{v}{4L}; \quad f_1 = \frac{1}{4L} \sqrt{\frac{T}{m/L}} \]

harmonics (only odd harmonics)

\[ f_n = \frac{v}{\lambda_n} = n \frac{v}{4L} = nf_1; \quad n = 1, 3, 5\ldots \]
Beat Frequency

effect of superimposing two “close” frequencies

\[ f_{\text{beat}} = |f_1 - f_2| \]

Example: “tuning a bottle” When a 440 Hz tuning fork is sounded as air is blown across the top of a partially filled soda bottle, a 4 Hz beat frequency is heard. If liquid is drained (by taking a *small* swig) and the experiment is repeated, a 5 Hz beat frequency is heard. What were the two frequencies of the musical bottle?