Physics Around Us 5
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Sound and Hearing

What is Sound?
• Sound is a compression wave
• The air is temporarily compressed to a slightly higher pressure than normal
• The wave front passes through the medium

In Two Dimensions
• The wave spreads out from a point source in a circular pattern
http://resource.isvr.soton.ac.uk/spcg/tutorial/tutorial/Tutorial_files/Web-basics-pointsources.htm

Longitudinal Wave
• Sound: air molecules move backwards and forwards in the same direction as the wave moves

Frequency and Wavelength
• The frequency of the wave and the wavelength are exactly the same as for a transverse wave

\[ \text{speed} = \text{wavelength} \times \text{frequency} \]

Speed of sound (varies with air pressure and temperature)

Wavelength: distance between crests
Frequency: number of crests which pass a fixed point per second
**Air**

- Composition
- Mostly nitrogen gas, N\textsubscript{2} and oxygen gas, O\textsubscript{2}

Plus water vapour, argon, carbon dioxide and other gases

**Intensity**

- We measure the “strength” of the sound with the quantity called Intensity, which has units of Power per unit area (Watts per square metre)

- The intensity decreases as you get further from the source, because the same power is spread over a larger area

**Scientific Notation**

- We often need to write very large or very small numbers in a compact fashion

- We use powers of 10

\[
100 = 10 \times 10 = 10^2
\]

\[
1000 = 10 \times 10 \times 10 = 10^3
\]

\[
10^9 = 1,000,000,000 \quad \text{1 followed by 9 zeros}
\]

**Perceived Loudness**

<table>
<thead>
<tr>
<th>Perceived Loudness</th>
<th>Intensity (watts/m\textsuperscript{2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold of hearing</td>
<td>10\textsuperscript{-12}</td>
</tr>
<tr>
<td>Rustle of leaves</td>
<td>10\textsuperscript{-11}</td>
</tr>
<tr>
<td>Whisper</td>
<td>10\textsuperscript{-9}</td>
</tr>
<tr>
<td>Watch ticking at 1 metre</td>
<td>10\textsuperscript{-7}</td>
</tr>
<tr>
<td>Radio (low)</td>
<td>10\textsuperscript{-7}</td>
</tr>
<tr>
<td>Quiet conversation</td>
<td>10\textsuperscript{-6}</td>
</tr>
<tr>
<td>Quiet motor at 1 metre</td>
<td>10\textsuperscript{-5}</td>
</tr>
<tr>
<td>Busy street traffic</td>
<td>10\textsuperscript{-4}</td>
</tr>
<tr>
<td>Door slamming</td>
<td>10\textsuperscript{-3}</td>
</tr>
<tr>
<td>Heavy truck, 15 metres away</td>
<td>10\textsuperscript{-2}</td>
</tr>
<tr>
<td>Lawnmower</td>
<td>10\textsuperscript{-1}</td>
</tr>
<tr>
<td>Pneumatic drill/Jackhammer</td>
<td>10\textsuperscript{1}</td>
</tr>
<tr>
<td>Jet engine</td>
<td>10</td>
</tr>
<tr>
<td>Rock Concert</td>
<td>10</td>
</tr>
</tbody>
</table>

**Decibel Scale**

- The decibel scale is a way of quantifying the Sound Intensity Level

- It is a non-linear scale (based on logarithms), but it simulates how the brain perceives the relative “loudness” of noises

Alexander Graham Bell, devised the Bel scale to analyse the performance of early telephones

1 Bel = 10 decibels
Perceived Loudness

<table>
<thead>
<tr>
<th></th>
<th>Intensity (watts/m²)</th>
<th>Intensity Level in dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold of hearing</td>
<td>$10^{-12}$</td>
<td>0</td>
</tr>
<tr>
<td>Rustle of leaves</td>
<td>$10^{-11}$</td>
<td>10</td>
</tr>
<tr>
<td>Whisper</td>
<td>$10^{-10}$</td>
<td>20</td>
</tr>
<tr>
<td>Watch ticking at 1 metre</td>
<td>$10^{-9}$</td>
<td>30</td>
</tr>
<tr>
<td>Radio (low)</td>
<td>$10^{-8}$</td>
<td>40</td>
</tr>
<tr>
<td>Quiet conversation</td>
<td>$10^{-7}$</td>
<td>50</td>
</tr>
<tr>
<td>Quiet motor at 1 metre</td>
<td>$10^{-6}$</td>
<td>60</td>
</tr>
<tr>
<td>Busy street traffic</td>
<td>$10^{-5}$</td>
<td>70</td>
</tr>
<tr>
<td>Door slamming</td>
<td>$10^{-4}$</td>
<td>80</td>
</tr>
<tr>
<td>Heavy truck, 15 metres</td>
<td>$10^{-3}$</td>
<td>90</td>
</tr>
<tr>
<td>Lawnmower</td>
<td>$10^{-2}$</td>
<td>100</td>
</tr>
<tr>
<td>Pneumatic drill/Jackhammer</td>
<td>$10^{-1}$</td>
<td>110</td>
</tr>
<tr>
<td>Jet engine</td>
<td>1</td>
<td>120</td>
</tr>
<tr>
<td>Rock Concert</td>
<td>10</td>
<td>130</td>
</tr>
</tbody>
</table>

**Why Use the Decibel Scale?**

- It is convenient, since it follows the way the human ear perceives loudness
  - A 1 dB change in the intensity level between two sounds corresponds approximately to the smallest change in loudness that the average listener with normal hearing can detect
- It gives numbers which are easy to understand 0-130 range

**Human Hearing**

- The ear is a sensitive detection system for sound waves
  - The shape of the ear is designed to guide sound waves into the auditory canal

- The human ear is not very sensitive below 800 Hz, or above 10,000 Hz

- The sound waves are funneled down the external auditory canal, and make the tympanic membrane (the ear drum) vibrate

- When the oval window vibrates it sends pressure waves down the liquid filled cochlear
The vibration of the ear drum moves the three bones in the ear known as the malleus, incus and stapes (hammer, anvil and stirrup). These tap on the oval window in the inner ear. The oval window is much smaller than the eardrum, so the effect is to magnify the amplitude of the wave. A small vibration of the eardrum causes a large vibration of the oval window.

The cochlea contains the sound sensors. It is a divided and coiled tube. Fluid makes the round window vibrate – this is needed to allow pressure waves to flow easily. The position along the membrane which is most stimulated by the compression sound wave is a measure of the frequency.

Perception of Pitch
- Mostly dependent on frequency
- Also depends on timbre and intensity

The mel scale and the pitch you hear:

https://en.wikipedia.org/wiki/Mel_scale

Localisation of Sound
- Which direction does the sound come from?
  - Difference in intensity
  - Sound arrives at the ears at different times, because it travels different distances

Limits of Human Hearing
- Humans can hear from around 20 Hz to 20,000 Hz (20 kHz)
- The upper limit is reduced as you get older
- A teenager can hear much higher pitched sounds than an older person

Subsonics
- Sounds below 20 Hz cannot be heard by people, so they are called **Subsonic** or **Infrasonic**
- For some of these frequencies we can sense the vibration in our bodies.
Subsonics

- Low frequencies and subsonics can be used theatrically to induce a sense of fear or unease.
  - Theme from Jaws
  - https://www.youtube.com/watch?v=ZvCI-gNK_y4
  - 17 Hz was used in an experiment in the UK in 2003 – 22% of participants reported symptoms including anxiety, uneasiness, extreme sorrow, nervous feelings of revulsion or fear, chills down the spine, and feelings of pressure on the chest!

Rhinoceros Speech

- Many animals communicate with grunts and sounds which are in the subsonic range
  - The Sumatran Rhinoceros grunts at 3 Hz

Ultrasonics

- Any sound vibration which cannot be heard by humans.
- The sound may be audible to other species.
- These waves easily propagate through human tissue
- They get strongly reflected at boundaries between different tissue types, so they can be used for imaging

Dog Whistles

- Dogs can hear much higher frequencies than humans – up to 46 kHz (compared to 20 kHz for young adult humans)
- It’s easy to make a whistle which sounds at frequencies which dogs can hear, but humans can’t.

Ultrasound and Medical Imaging

- Uses sound waves at the 1 MHz range
- Sometimes called a sonogram

- Advantages:
  - Non-invasive
  - Very safe
  - Shows up boundaries in soft tissues which are not visible in X-ray imaging.
  - Three dimensional imaging is now possible

http://pregnancy.about.com/od/fetus/ig/3D-Ultrasound-Gallery/
Sonar

• An acronym for Sound Navigation And Ranging
• A sound pulse (“ping”) is sent out and reflected

http://www.youtube.com/watch?v=DI9bx_V5inhE

Sound of Music

• Music is a set of complex sounds
• The Pitch in music corresponds to the frequency.
• Individual musical instruments have their own “sound” characteristics, which also depend on overtones, echo/reverberation, how long each note is sustained etc.

Creating a Sound

• We need something which vibrates – this disturbs the air with the same frequency, and creates the sound wave.
  – Vibrating guitar string
  – Loudspeaker cone

Electromagnet shakes the cone

• The shape of the wave plays a big part in how it sounds – even if the frequency (pitch) is the same

Sine wave
Triangle
Sawtooth
Square wave

http://onlinetonegenerator.com/432Hz.html

Fourier’s Theorem

• Any wave can be made by adding together combinations of sinusoidal waves:

Jean Baptiste Joseph Fourier (March 21, 1768 - May 16, 1830)
By varying the frequency and the amplitude of the sine waves, it is possible to build up any desired wave from an infinite series of simple waves.

https://lpsa.swarthmore.edu/Fourier/Series/WhyFS.html

Standing Waves

- A standing wave may occur if a travelling wave in a medium is reflected back on itself
  http://www.walter-fendt.de/ph14e/stwaverefl.htm
- Only waves which have a wavelength which is an integer or half integer value of the length of the medium do this.
- All other waves on the string die away
  https://www.youtube.com/watch?v=gi7KnvDnxR8

String Instrument Oscillations

Musical Terminology

<table>
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<tr>
<th>Harmonic</th>
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<tr>
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The harmonics are defined by quantum numbers \( n = 1, 2, 3 \ldots \)

Percussion Instruments: Drum Skin Oscillations

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Wind Instruments: Standing Waves in Air Pipes

- Open at both ends: flute
- Open at one end: clarinet

Air Pressure Waves

- The harmonic series of frequencies are all multiples of the first harmonic (fundamental)

\[ f_n = n f_1, \quad n = 1, 2, 3, \ldots \]

- A classical physical system with quantized natural frequencies
Didjeridoo
• A musical instrument used by the Indigenous peoples of Australia.
• A long open tube, which is blown into at one end, other end resting on the ground
• It acts like a pipe with one end closed (by the mouth and lips of the player)

https://www.youtube.com/watch?v=GCOPI7lbPkc

Sound Spectrum from a Dijeridoo

Pipe Organ
• Standing waves can also be produced when air is blown down a tube. The tube can be open at both ends, or closed at the far end
• We can visualize the standing waves using a Rubens tube

https://www.youtube.com/watch?v=pWekXMZJ2zM

Wind Instruments
• These create the sound by creating standing waves in a tube

Change the notes by opening or closing holes in the side or changing the length of the tube.

http://www.youtube.com/watch?v=LJwuBFQ8Auk  James Galway Flute

Beats
• If two waves of approximately the same frequency (within ~ 20Hz) are in the same place at the same time, they produce a phenomenon known as beating.

http://onlinetonegenerator.com/binauralbeats.html
There are now two frequencies associated with the combined wave:
- The frequency of the blue waves, which is the average of the two original frequencies.
- The frequency of the red modulation wave, which is the difference between the two original frequencies.

We use the beat frequency to tune musical instruments:
- We use a tuning fork of known frequency/pitch and then play the instrument at the same pitch.
- When the beat disappears, both frequencies are the same.

Human Voice:
- How we speak:
  - Our windpipe acts as a pipe organ.
  - Our vocal cords modulate the air in the windpipe to give us different frequencies.
  - We use the shape of our mouths, tongue position, lips, and cheeks to annunciate (shape the sound wave).

Making Your Voice Sound Strange!
- If you inhale a gas such as H\textsubscript{2} (low density) or SF\textsubscript{6} (high density), the speed of sound in your windpipe changes.
  - The wavelengths produced by the voice remain the same. If the density of the gas decreases, so does the speed of sound and hence so does the frequency.
  - So you sound like Donald Duck if you inhale Helium.

The Doppler Effect:
- The change in frequency (pitch) detected by an observer because the sound source and the observer have different velocities with respect to the medium of sound propagation.

Do not attempt to breath the helium in directly from a pressurized tank or cylinder.
- High pressure helium bubbles in the bloodstream can be fatal.

\textit{http://www.youtube.com/watch?v=d-XbjFn3aqE}
• If you are listening to the source coming towards you, the sound waves are compressed (shorter wavelength, higher frequency)

• If you are listening to a receding source, the sound waves are elongated (longer wavelength, lower frequency)

Doppler Flow Meter
• Use the Doppler shift to determine the speed of flow of a fluid in a pipe

Clinical Applications
• For determining the blood flow rate in blood vessels near to the skin
  • 5 Mhz frequency
  • Red blood cells reflect the sound, and there is a Doppler shift in the reflected sound of for red blood cells moving at 0.1 m/s
  • Good for detecting narrowed blood vessels, where flow rates are greater