Sound Physics & Audition Basics

Sound Waves

Sound Waves: Vibrations of moving air created when an object's movement causes surrounding air molecules to fluctuate in pressure.

Mechanism

- When an object vibrates, it creates alternating areas of:
- **Condensation:** High-pressure zones where air molecules are compressed.
- **Rarefaction:** Low-pressure zones where air molecules are pulled apart.
- This pattern of pressure fluctuations travels away from the source at ~700 mph (the speed of sound).

Wave Relationship Formula

$$v = f \times \lambda$$

v = speed of sound (~343 m/s in air)

f = frequency (in Hz)

λ = wavelength (in meters)

Example Problem

A sound has a frequency of 440 Hz (the note 'A'). What is its wavelength in air?

$\lambda = v / f$

$\lambda = 343\ m/s / 440\ Hz$

$\lambda \approx 0.78$ meters

Annotation: Higher frequencies result in shorter wavelengths. This is why a high-pitched piccolo produces much smaller sound waves than a low-pitched tuba.

Audition (Hearing)

Audition: The process by which the human ear transduces (converts) fluctuations in air pressure into neural signals interpreted by the brain.

Human Hearing Range

- **Frequency:** Humans can typically hear vibrations between **20 Hz and 20,000 Hz**.
- **Wavelength:** This corresponds to detectable wavelengths from approximately **17 meters** (for 20 Hz) down to **1.7 centimeters** (for 20,000 Hz).

3 Physical Dimensions of Sound

1. Loudness (Amplitude)

Loudness: The perception of sound intensity, which corresponds to the amplitude of the sound wave. It's the relative difference in pressure between condensation and rarefaction zones.

- **High Amplitude** → Densely Packed Condensations → **LOUD** Sound
- **Low Amplitude** → Loosely Packed Condensations → **SOFT** Sound
- Relates to how far the sound energy travels.

2. Pitch (Frequency)

Pitch: The perception of how "high" or "low" a sound is, corresponding to the frequency of the sound wave.

- **High Frequency** → More cycles per second → **HIGH** Pitch
- **Low Frequency** → Fewer cycles per second → **LOW** Pitch
- Measured in Hertz (Hz).
- In the cochlea, different frequencies are processed at different locations.

3. Timbre (Complexity)

Timbre (pronounced "TAM-ber"): The quality or "color" of a sound that distinguishes different sound sources, even when they have the same pitch and loudness.

- Arises from the complexity of the sound wave (its unique shape).
- A pure tone is a simple sine wave. Most sounds are complex waves, composed of a fundamental frequency plus multiple overtones (harmonics).

Advanced Concepts: Loudness & Pitch

Measuring Loudness: The Decibel (dB)

Decibel (dB): A logarithmic unit used to measure sound intensity level. The logarithmic scale better reflects how human ears perceive loudness.

- **0 dB:** The threshold of human hearing.
- A **10 dB increase** corresponds to a **10-fold increase in intensity** and is perceived as roughly **twice as loud**.
- **60 dB:** Normal conversation.
- **120 dB:** Pain threshold (e.g., jet engine).

Sound Intensity Level Formula

$$L = 10 \times \log_{10}(I / I_0)$$

L = Sound level in decibels (dB)

I = Sound intensity (W/m²)

I_0 = Reference intensity (10^{-12} W/m²)

Example Problem

A quiet library has a sound intensity of 10^{-9} W/m². What is its decibel level?

$$L = 10 \times \log_{10}(10^{-9} / 10^{-12})$$

$$L = 10 \times \log_{10}(10^{3})$$

$$L = 10 \times 3 = 30 \text{ dB}$$

Annotation: This shows how a tiny absolute intensity value corresponds to a familiar decibel level for a quiet environment.

Inverse Square Law for Sound

Inverse Square Law: Describes how the intensity of sound decreases as the distance from the source increases. Specifically, intensity is inversely proportional to the square of the distance.

Inverse Square Law Formula

$$I \propto 1 / r^2$$

$$(I_1 / I_2) = (r_2^2 / r_1^2)$$

I = Intensity

r = distance from source

Example Sketch

If you double your distance from a speaker (from 2m to 4m), what happens to the intensity?

Distance is multiplied by 2.

Intensity is divided by $2^2 = 4$.

The sound will be only **one-quarter** as intense.

Annotation: This explains why sounds get faint so quickly as you move away from them. It's a fundamental principle in acoustics and audio engineering.

Pitch, Octaves, and Music

Octave: In music, an octave is the interval between one musical pitch and another with double its frequency.

- If the note **A4** has a fundamental frequency of **440 Hz**:
- The note one octave higher (**A5**) has a frequency of **880 Hz** (440 x 2).
- The note one octave lower (**A3**) has a frequency of **220 Hz** (440 / 2).
- Notes an octave apart are perceived by humans as being the "same" note, just higher or lower in pitch.

Frequency Ranges (Approx.)

- **Sub-bass:** 20 - 60 Hz
- **Bass:** 60 - 250 Hz
- **Midrange:** 250 Hz - 2 kHz (Human voice)
- **Upper Midrange:** 2 kHz - 4 kHz
- **Presence:** 4 kHz - 6 kHz
- **Brilliance:** 6 kHz - 20 kHz

Timbre, Complexity & Doppler Effect

Timbre & Wave Complexity

Fourier's Theorem: Any complex, periodic waveform can be broken down into a sum of simple sine waves of different frequencies, amplitudes, and phases.

- **Fundamental Frequency:** The lowest frequency in the complex wave. It determines the perceived pitch of the note.
- **Overtones/Harmonics:** Higher frequency sine waves that are whole-number multiples of the fundamental.
- The unique combination and intensity of these harmonics determine the instrument's **timbre**.

Visualizing Timbre (Sketch)

Imagine building a sound wave:

[Simple Sine Wave @ 100Hz]
(This is the fundamental)
+
[Smaller Sine Wave @ 200Hz]
(This is the 2nd harmonic)
+
[Even Smaller Sine Wave @ 300Hz]
(This is the 3rd harmonic)
↓
[A Complex, Jagged Waveform]
(This is the final sound with a unique timbre)

Annotation: A flute produces a sound that is very close to a pure sine wave (few harmonics), while a trumpet has many strong, high-frequency harmonics, giving it a "bright" or "brassy" timbre.

The Doppler Effect

Doppler Effect: The change in frequency of a wave in relation to an observer who is moving relative to the wave source.

- As a sound source **approaches** an observer, the sound waves are compressed, leading to a **higher perceived frequency (higher pitch)**.
- As a sound source **moves away** from an observer, the sound waves are stretched, leading to a **lower perceived frequency (lower pitch)**.

Doppler Effect Formula (Moving Source)

$$f' = f \left(v / (v \mp v_s) \right)$$

f' = observed frequency
f = emitted frequency
v = speed of sound
v_s = speed of the source
Use (-) for approaching, (+) for receding.

Doppler Effect Example

Example Problem

An ambulance with a 1200 Hz siren is approaching you at 25 m/s. The speed of sound is 343 m/s. What frequency do you hear?

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f' = 1200 × ( 343 / (343 - 25) )
f' = 1200 × ( 343 / 318 )
f' = 1200 × 1.0786
f' ≈ 1294 Hz
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Annotation: You hear a higher pitch (1294 Hz) than the actual siren (1200 Hz) because the ambulance is moving towards you. If it were moving away, you would use (343 + 25) in the denominator, resulting in a lower perceived pitch.

Sonic Boom

Sonic Boom: When an object travels faster than the speed of sound (supersonic), it outruns its own sound waves. These waves build up into a single, high-pressure shockwave that is heard as a loud "boom" when it passes an observer.