Chapter 05: Wave Motions and Sound

Sound is transmitted as increased and decreased pressure waves that carry energy. Compared to the soft sounds you might hear on a calm day in the woods, the sounds from a crashing waterfall can carry up to a million times more energy.

Section 5.1: Forces and Elastic Materials

Elasticity

- It's not just the stretch, it's the snap back
- An elastic material will return to its original shape when stretched
- An inelastic material will either break (brittle like glass) or remain deformed (plastic like putty)

Hooke's Law: $F = -kx$

- F: Force exerted by the spring
- k: Stiffness of spring (higher k, harder to stretch)
- x: Amount by which spring is stretched
- Negative: Spring pushes or pulls in the direction opposite its displacement

Forces and Vibrations

- Vibration or oscillation? Meh, this time they really are interchangeable
- Back-and-forth (up-down, side-to-side, whatever) motion: you keep doing it, but you don't get anywhere
- Periodic refers to the repeat: same pattern, same amount of time

Describing Vibrations

- Amplitude (m): A = maximum displacement from equilibrium
- Cycle (no units): One full pattern of repetition (back to where you started, ready to repeat the whole thing over again)
- Period (s): T = time to complete one full cycle
- Frequency (1/s=Hz): f = cycles completed per second ($f = \frac{1}{T}$)

Section 5.2: Waves

What Makes It A Wave?

- Oscillation (vibration) by itself ≠ wave
- Propagation (forward motion) ≠ wave
- Oscillation + propagation = wave

Kinds of Mechanical Waves

- Longitudinal: Oscillation is parallel to propagation
- Transverse: Oscillation is perpendicular to propagation

Propagation Through a Medium

- Most waves (not all!!!) require a medium to travel through
- Matter does not propagate! The energy propagates!
- Molecules vibrate, but do not propagate along with the wave

The Matter Matters

- Solid: Can transmit either longitudinal or transverse waves
- Liquid: Transmits longitudinal waves (only at surface can transverse propagate)
- Gas: Can only transmit longitudinal waves

Waves in Air

- Sound waves through air must be longitudinal
- Air molecules vibrate, but do not translate
- Compression (condensation): Molecules of the medium get slightly closer together than average (density increase)
- Rarefaction: Molecules of the medium get slightly farther apart than average (density decreases)

Section 5.3: Describing Waves

Parts of A Wave

- Amplitude (m): A = height of the crest or depth of the trough

- Wavelength (m): $\lambda =$ distance crest–crest or trough–trough
- Period (s): T = time to complete one cycle of oscillation
- Frequency (Hz): f = cycles per second

Motion of a Wave

- Frequency describes rate of oscillation: $f = \frac{1}{T}$
- Wave speed describes rate of propagation: v = distance/time $= \frac{\lambda}{T} = \lambda f$

Section 5.4: Sound Waves

Sound Waves in Air and Hearing

- To be heard, a sound must have an audible frequency
- Human ears: Typically 20Hz $\leq$ f $\leq$ 20,000Hz is the audible range
- Infrasonic: Frequency below human hearing (f $\lesssim$ 20Hz)
- Ultrasonic: Frequency above human hearing (f $\gtrsim$ 20,000Hz)

Different Person, Different Ears, But Same Mechanism

- You perceive a lower frequency sound as a lower pitch (higher f, higher pitch)
- Vibrating air molecules collide with your eardrum, set up mechanical vibration through the system
- Cochlea has tiny, tiny little hairs (cilia) which are tuned (length/thickness) for specific frequencies
- Damage the cilia, you lose those frequencies–forever (the cilia don't regenerate, can't be fixed)

Medium Required

- Sound waves are matter waves: They cannot travel through vacuum, there must be molecules of something to propagate the energy
- Different medium, different speed
- Fluids: Less massive molecules mean faster speeds, given the same amount of energy
- Solids: Elasticity is much more important than density for rapid propagation

Velocity of Sound In Air

- Speed of sound = 331 m/s (but only if it's dry air at 0°C)
- Warm air is fast air: Warm air molecules are already moving faster than cold air molecules ($v = 331 + 0.6T$)
- Humid air is fast air: Water molecules are less massive than air molecules, so they are faster

Reflection and Refraction

- What happens when a sound wave runs into an obstacle?
- An obstacle in this sense means a change in medium, like warm to cold air, or air to water, or air to solid matter
- Absorption, transmission, reflection

Refraction

- Wave can keep moving through the new medium, but it's speed changes (warm air = faster than cold air, for example)
- Change in speed causes a change in direction of propagation: Wave bends
- Change in direction: Wave always bends toward the slower medium (away from the faster medium)

Reflection

- Wave strikes a boundary and bounces off: Only one rule applies, angle in = angle out
- Smooth, hard surfaces typically bounce sound waves better than soft or highly textured surfaces
- Acoustic design: Control how much sound gets absorbed, and where you want sound to be reflected

Echoes

- If you hear the sound reflection, that's an echo
- Echolocation: Bounce a sound wave off an object (on purpose), and use the time lapse to figure out where the object is
- Bats scream at insects "Get in my belly!" but the frequency is too high for you to hear

Interference

- This is how you know for sure that waves are about energy, and not matter, propagation!
- Matter: You can't put two objects in the same place at the same time
- Energy: You can put two waves in the same place at the same time

Constructive Interference

- In phase: Waves match up (crest for crest, or compression for compression) and reinforce
- The sound is amplified: Increase in amplitude, but same frequency (pitch)
- This is why you sound fantastic when you sing in the car: Your voice reflected off the windshield interferes constructively

Destructive Interference

- Out of phase: Waves line up crest-trough (rarefaction-compression), and cancel out
- The sound is minimized: It might be partially cancelled, or completely cancelled
- This is how noise-cancellation headphones work

Beats

- Multiple sources at multiple frequencies will predictably line up (if you know the frequencies, you can calculate it)
- Turn signals: When you listen to your signal click and watch the car in front of you blink, you notice they move into phase (same time for click/blink), then slowly move out of phase, the back into phase

Section 5.5: Energy of Waves

Sound Intensity

- Energy (J): Sound wave is the transmission of energy through a medium
- Per Time (1/s): The sound wave keeps coming for some duration of time
- Over Area ($1/m^2$): That sound wave hits the whole surface of your eardrum, not just at a point; the energy is spread out over the surface
- Intensity = (energy per time)/area = $(J/s)/m^2 = W/m^2$

How Loud Is That Sound?

- Your ears are not linear; they are logarithmic!
- You do not perceive a sound with twice the intensity (hence twice the energy) as being twice as loud
- Everybody's ears are different, but in general it takes 10× the energy to perceive a sound as "twice as loud"

Decibel Scale

- Combines the objectively measurable (intensity) and the subjectively perceived (your hearing)
- Decibel scale is logarithmic because that's how your ears operate
- $0\text{dB} = \text{threshold of hearing } I_o \simeq 1 \times 10^{-12}\frac{\text{W}}{\text{m}^2}$
- $120\text{dB} = \text{threshold of pain } I_p \simeq 1\frac{\text{W}}{\text{m}^2}$

Resonance

- Find the natural frequency of an object an amplify it!
- Natural frequency: Tuning fork is an obvious example; the fork wants to vibrate at a certain frequency, because of what it's made of, the shape/length of the tines

- Amplify the natural frequency: Apply a force with that same frequency (either on purpose or by accident)

Section 5.6: Sources of Sound

Music vs Noise

- Noise: Random frequencies, different amplitudes–you might have trouble making sense of the mess
- Pure Tone: A single frequency (like a tuning fork)
- Musical Note: You can tell the difference between the same note (same frequency) played on different instruments–why?

Vibrating Strings

- Guitar, piano, banjo: Sounds very different, but mechanism is the same
- Same mechanism even if you don't have a string: Flute, saxophone, bassoon
- Vibrating a column of air gives you music the same way vibrating a string does

Standing Waves

- String or air column: Pick one, doesn't matter which
- One end fixed, the other end either free (flute) or fixed (guitar)
- Vibrate the medium at its natural frequency (blow or strum)
- The fixed end will reflect an incoming wave, and flip it

Nodes and Anti-Nodes

- Fixed ends are nodes: The amplitude is always zero
- Free ends are anti-nodes: The amplitude is maximum
- The wave and its reflection will interfere

Overtones

- Fundamental frequency: Nodes at both ends, length of string = exactly ½ wavelength ($l = \frac{1}{2}\lambda$)
- First overtone: Nodes at both ends, length of string = exactly 1 wavelength ($l = \lambda$)
- Second overtone: Nodes at both ends, length of string = exactly $(1 + \frac{1}{2})\lambda$ ($l = \frac{3}{2}\lambda$)
- Adjust the length of the string by holding it down

Sounds From Moving Sources

- The assumption we have been making (right up to this point) is that whatever is making the sound (source) and whatever is hearing the sound (receiver) are both stationary with respect to each other
- What is the source gets closer or farther from the receiver?
- What if the receiver isn't staying put?
- What is both source and receiver are moving?

Doppler Effect

- It does not matter whether the source, receiver, or both are in motion
- Decrease the distance (approach): Receiver will perceive an increase in frequency
- Increase the distance (recede): Receiver will perceive a decrease in frequency
- Source (moving or not moving, does not matter) does not change the true frequency it is emitting

Not Just For Sound Waves!

- Light waves do this as well: Doppler shift (red shift or blue shift) is used in Astronomy to determine radial velocity of distant stars, rotation rates, and is even a method for detecting extrasolar planets!
- Doppler Radar: Uses radio waves bounced off of storm systems (clouds, falling rain, hail, etc.) to determine the precise location, how much precipitation, how fast the storm is tracking, and whether it is spinning (and in which direction)