Sound Waves
Chapter 13

General Characteristics

- Longitudinal wave; requires elastic medium for propagation
- Series of compressions and rarefactions in the medium (what the sound is passing through)
- Elastic forces of the medium transfer wave energy from particle to particle

Sound Transmission

- Must have a medium for transmission: sound will not travel through a vacuum
- Usual medium is air, but sound travels better in liquids and solids
- Elasticity of medium is most important property
- Usually denser media transmit sound better

Sound Production

- Sound is produced by vibration in an elastic medium
- Energy of vibration is passed to particles of medium
- As object pushes against medium it creates compressed area; as it moves back, it creates rarefied area
- Change in amplitude of vibration changes amount of compression, but not frequency
- Vibrating source can be string, reed, air column, vocal chord, etc.

The Sonic Spectrum

- Frequency range over which sound waves can be transmitted
- Upper limit determined by particle spacing of medium
- For air and other gases upper limit is about 1 billion Hz; higher in liquids & solids
- No clearly defined lower limit

The Audio Spectrum

- The frequency range of sound waves that can be heard by humans
- Depends on hearing of listener
- Audible sounds range from about 20 Hz to 20 kHz
- Sounds below audio spectrum called *infrasonic*; above it called *ultrasonic*

Ultrasound

- High frequency sound used for imaging and cleaning
- "Ultrasound" means $f > 1\text{MHz}$ so $\lambda < 1.5$ mm
- Short wavelength means greater detail can be "seen" in reflected image

Sound Reflection

- Clear distinct reflection of sound produces an echo
- Multiple reflections from nearby surfaces produce reverberation
- Sound echoes can be used for imaging: bats, dolphins, SONAR, ultrasound imaging

- Ultrasound physics is similar to sonar used by submarines and the sonar used by bats for navigation. Bats and submarines both use the time it takes for the echo to be reflected back to determine their distance from the measured objects.

Speed of Sound

- At 0^o C, sound travels 331.5 m/s in air
- Speed increases about 0.6 m/s for each degree above zero
- Speed of sound is about 4 times faster in water, much faster in elastic solids like steel
- In aviation, speed of sound is designated Mach 1; 2 X speed of sound is Mach 2

Sound Properties

- Intensity: perceived as loudness
- Frequency: perceived as pitch
- Harmonic Content: perceived as tone or quality

Intensity and Loudness

- Intensity: time rate of flow of sound energy through a unit area
- $I = P / A$ where P is power in watts and A is area in square meters.
- Intensity (and power) is proportional to square of wave amplitude
- Sound wave spreads in spherical pattern from source so intensity depends inversely on square of distance from source
- Loudness is physiological response to intensity and depends on sensitivity of listener
- Human hearing more sensitive to some frequencies than others

Relative Intensity

- Intensity is measured with instruments with respect to the faintest audible sound: the *threshold of hearing*, 10^{-12} W/m^2 (I_0)
- Relative intensities placed on logarithmic scale called the *decibel scale*
- $\beta = \log(I/I_0)$ where β is relative intensity in decibels (dB)
- Relative intensity of 120 dB called *threshold of pain*
- A soft whisper is about 10 dB
- Normal conversation is about 60 dB
- Thunderclap about 110 dB

Frequency and Pitch

- Pitch is determined by frequency of vibration; allows sounds to be placed in musical scale
- Noise is sound without discernible pitch; has non-periodic waveform
- Frequencies of ratios 2:1, called octaves

The Doppler Effect

- A change in frequency due to relative motion between wave source and observer.
- Applies to all wave types
- With sound waves, effect is change of pitch heard when either source or listener are moving (or both)

- Apparent frequency and pitch higher than actual frequency when source and listener move closer
- Apparent frequency and pitch lower when source and listener move apart
- Used to measure speed of planets, stars, cars when applied to light or radar waves.

Doppler Effect Equations

- Listener moving : $f' = f(v \pm v_D)/v$ where v_D is speed of listener (detector), f is actual frequency of source and f' is frequency heard (detected)
- Source moving: $f' = f\, v / (v \pm v_S)$ where v_S is speed of source

Sound Quality

- Harmonic content determines sound quality or tone.
- Presence of many high harmonics produces bright tone (treble);
- Different instruments producing same fundamental frequency sound different because of different harmonics

Laws of Strings

- Frequency is inversely proportional to string length: $f / f' = l'/l$
- Frequency is inversely proportional to string diameter: $f / f' = d'/d$
- Frequency is directly proportional to square root of tension: $f / f' = (T/T')^{1/2}$
- Frequency is inversely proportional to string density: $f / f' = (D'/D)^{1/2}$

Forced Vibrations

- Causing a second object to vibrate by contact with another vibrating object
- Vibrating strings & reeds produce little sound; transmit vibration to larger object to increase sound: body of instrument, sounding board, vibrating air column

Resonance

- All objects have certain natural frequencies of vibration
- When forced vibration occurs at natural frequency of object, resonance occurs and vibration amplitude is greatly increased
- Can be desirable or not

Vibrating Air Columns

- Basis of organ pipes, flute, clarinet, trumpet, etc.
- Air column resonates with applied frequency depending on its length; wave is reflected at opposite end of tube creating standing wave at resonant frequency
- Can be open ended or closed ended

Fundamental Tones and Harmonics

- The lowest frequency produced by a vibrating object is the *fundamental*
- Produced by strings vibrating as a whole
- Strings and other vibrating objects can vibrate in segments producing *harmonics*: frequencies that are whole number multiples of the fundamental
- Fundamental is called first harmonic
- 2 x fundamental frequency is second harmonic, etc.

- Music term for harmonic is overtone; 2nd harmonic is 1st overtone, etc.
- Most sounds are combinations of fundamental and harmonics

Closed Ended Tubes

- Standing wave in closed tube has node at closed end, anti-node at open end
- Fundamental frequency has approx. 1/4 of wave inside tube (node to anti-node)
- Wavelength about 4 x length of tube
- Resonance will occur at all harmonics that have same node/anti-node arrangement
- Closed end tubes thus resonate at odd quarter wavelengths and produce only odd numbered harmonics

Open Ended Tubes

- Standing wave in open ended tubes have antinode at each end
- Wavelength of fundamental is approx. 2 x length of tube since about half the wave is contained in tube
- Harmonics with antinode at each end will also be produced, thus open ended tubes produce all harmonics

Interference and Sound Waves

- Like all waves, sound waves of the same frequency can cause constructive or destructive interference
- When waves are exactly opposite, unwanted sound can be analyzed and removed
- Two sound sources can produce interference pattern resulting in uneven sound

Beats

- Two waves of nearly the same frequency sounded simultaneously will interfere with each other
- Alternating constructive and destructive interference causes amplitude pulsation
- Sound heard is average frequency with beat frequency equal to difference in two sound frequencies
- Used to tune instruments