Chapter 7 Sound

7.0 Introduction

The physics of sound is a captivating and intricate field that explores the fundamental principles governing the generation, propagation and perception of auditory phenomena. Sound waves are longitudinal mechanical waves; as such, they oscillate parallel to the direction of the propagation i.e. the direction of the disturbance. Sound waves, like all longitudinal waves, require a medium, which can be a solid, a liquid or a gas, to propagate and are characterized by variations in pressure that create compressions and rarefaction which form a rhythmic pattern.

Some of the key parameters of a sound wave include its frequency, which determines the pitch we perceive and its amplitude which determines the intensity, or how loud it sounds. Remarkably, the human ear can detect an extensive range of frequencies which allows us to experience a diverse spectrum of sounds. The average range of human hearing is between 20 Hz and 20 kHz (or 20 Hz – 20,000 Hz).

Understanding the physics of sound is not only fundamental for comprehending the mechanics of musical notes and environmental noises, it is also crucial for applications that range from acoustics and audio engineering to medical diagnostics and industrial monitoring. This chapter explores the physics of sound and provides some insight into their applicability to various interdisciplinary fields.

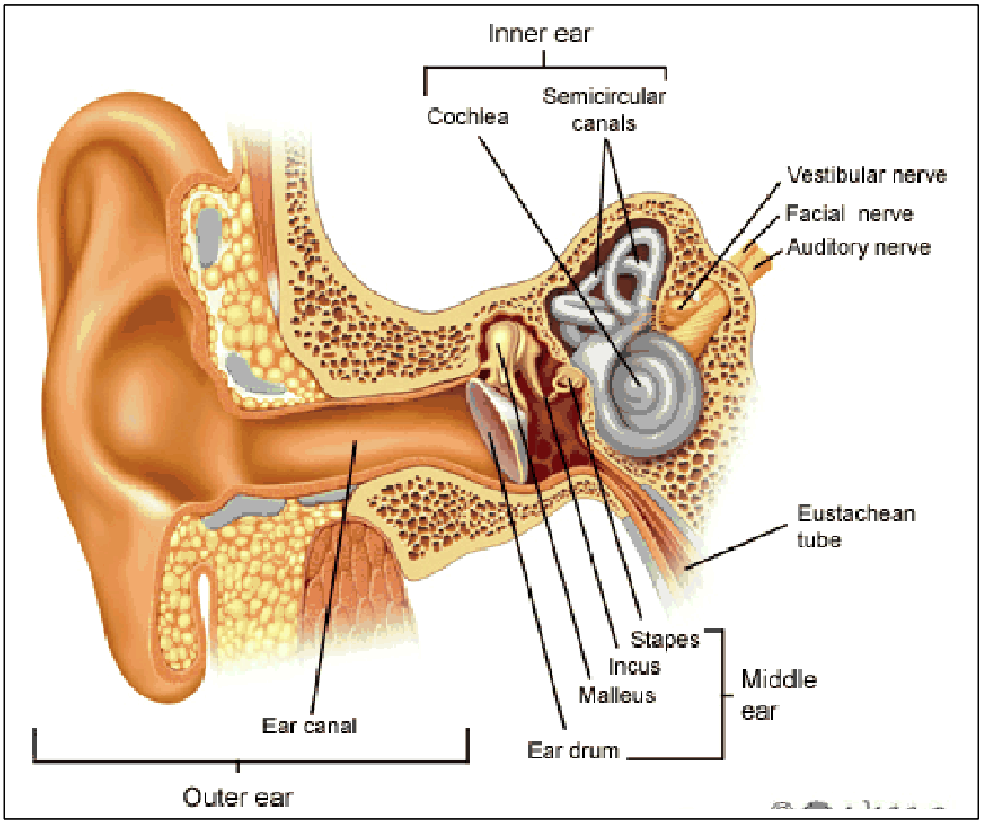
7.1 How We Hear

We will begin our discussion of sound by examining the human ear and how we hear. The ear is a remarkable sensory organ that allows us to perceive and interpret sound. It plays a vital role in our ability to communicate, enjoy music, and navigate the world around us. The human ear functions as a complex system that efficiently transmits and amplifies sound waves. Our sound perception and ability to understand sounds is based on the structure of our ears.

The Human Ear

The human ear is divided into three main parts: the *outer ear*, the *middle ear*, and the *inner ear*. The ***outer ear*** consists of the pinna (visible part of the ear) and the ear canal. The **pinna** helps to collect sound waves and funnel them into the **ear canal**, which leads to the middle ear. The ***middle ear*** houses the **tympanic membrane (eardrum)** and three very small bones or **ossicles** namely the **malleus (hammer)**, the **incus** (**anvil)** and the **stapes (stirrup)**. The ossicles are the three smallest bones in the human body.

Because sound waves are longitudinal, the series of compressions and rarefactions travel parallel to a disturbance or vibration. When a sound wave reaches the eardrum, the vibration is transferred to the eardrum causing it to begin to vibrate at an amplitude matching the energy of the sound wave. The vibrations from the eardrum are transmitted through the ossicles, the ossicles amplify the sound and transmits it to the inner ear.



Structure of the Human Ear (www.myvmc.com)

The ***inner ear*** consists of the vestibular system, the cochlea and the auditory nerve. The function of the **vestibular system** is to detect the position and movement of our head in space. This allows us to coordinate our eye movements, posture and equilibrium which help us to maintain our balance and spatial orientation. The **eustachian tube** is located in the inner ear and connects the middle ear to the back of your nose and throat. Its purpose is to help drain any fluid and to equalize air pressure in your ears.

The **cochlea** is a fluid-filled spiral-shaped structure which is responsible for converting sound vibrations into electrical signals. When the vibrations are transmitted from the middle ear enter the they cause the fluid within the cochlea to move which stimulates the hair cells. These hair cells convert the mechanical vibrations into electrical signals, which are then transmitted to the brain via the **auditory nerve**. When the electrical signals arrive at the brain, they are processed and interpreted allowing us to perceive and understand the nature of the sounds.

	Hearing Range
Humans	20 Hz to 20,000 Hz (20 Hz – 20 kHz)
Dogs	40 Hz to 60,000 Hz (40 Hz – 60 kHz)
Cats	48 Hz to 85,000 Hz (48 Hz – 85 kHz)
Bats	100 Hz to 200,000 Hz (100 Hz – 200 kHz)
Elephants	16 Hz to 12,000 Hz (16 Hz – 12 kHz)
Dolphins	75 Hz to 150,000 Hz (75 Hz – 150 kHz)
Owls	200 Hz to 12,000 Hz (200 Hz – 12 kHz)
Rats	250 Hz to 80,000 Hz (250 Hz – 80 kHz)

Hearing Ranges of Selected Animals

Hearing ranges provide animals with the ability to detect sounds relevant to their survival, such as communication signals, the approach of predators or prey, and environmental cues. Dogs have a broader hearing range compared to humans and are particularly sensitive to higher frequencies, allowing them to hear sounds like a dog whistle. Cats have a wider hearing range than both humans and dogs. They have the remarkable ability to detect high-frequency sounds which makes them effective hunters. Animals that hear in the ultrasonic range such as bats and dolphins use echolocation echoes to navigate and locate prey. While elephants and whales hear infrasound range and use low-frequency sounds for communication over long distance. Adaptations in hearing capabilities are often closely tied to an animal's ecological niche and behavior.

Sound Perception and Pitch

Our brains play a crucial role in sound perception so we although we hear sounds with our ears, we actually need our brains to listen since the brain processes and deciphers what we hear. This is what gives us the ability to *tune out* sounds or ignore background noise. When the electrical signals from the auditory nerve reach the brain, they are processed and interpreted, allowing us to perceive and understand sounds.

The brain interprets the frequency of sound waves as the **pitch.** Higher frequency waves are perceived as high-pitched and louder sounds, while lower frequency waves are perceived as low-pitched and softer sounds.

Beats

As discussed previously, waves interference occurs whenever two or more waves meet or overlap with each other. When waves meet in phase, that is when the crests and troughs of two waves align with each other, they constructively interfere with each other. Constructive interference increases the amplitude of the resulting wave. The alignment of the wave's crests and troughs results in the increase and decrease in its frequency leading to a regularly paced rise and fall in the level of the sound generated by the wave. The pattern of regular even-paced pulses creates **beats**.

Music, Melody and Noise

A melody is a sequence of pitches that form a recognizable musical line and creates the primary structure of a piece of music. When a series of different pitches are combination of played simultaneously it is referred to as a harmony. Melodies and harmony involve chords, chord progressions and the interplay between multiple voices or instruments. The arrangement of sounds in time is the rhythm and includes other aspects of music such as beat, tempo and duration of notes of duration. Rhythm gives music its groove, energy and sense of forward motion.

When pitches are combined in a disjointed and/or dissonant manner, it is referred to as noise. Noise can be described as any random or disruptive sound and is characterized by its irregular wave forms that lack the organized patterns normally associated with musical tones or speech. Noise can arise from various sources including machinery, traffic, industrial processes and environmental factors.

Loudness and Intensity

In everyday conversation, the terms loudness and intensity are frequently used interchangeably. However, while the two terms are related, they are not the same. Specifically, intensity is the actual measurable amplitude of a soundwave, while loudness is based on how a sound is perceived. As such, loudness is based on perception and intensity is measurable but how loud a sound seems is closely related to its intensity and the greater the intensity – the louder the sound.

The intensity of a sound is a function of the amount of energy carried by a sound wave. Sound intensity measures how quickly the energy carried by a wave is transferred through a given area. Intensity is calculated as the quotient of the power and the area.

$$\boldsymbol{Intensity = \frac{power}{area}}$$

$$\boldsymbol{I = \frac{P}{A}}$$

Sound intensity is measured in decibels (dB). The decibel scale is a logarithmic scale that expresses the ratio of one intensity to another and was chosen for sound measurement because it corresponds to human perception of loudness. Because the scale is logarithmic, each 10 - decibel increase in the scale represents a 10-fold increase in intensity. This means that a sound that is measured at 50 decibels is 10 times as intense as a sound with a level of 40 decibels.

It's important to note that prolonged exposure to sounds above 85 dB can potentially cause hearing damage, and exposure to sounds above 120 dB can be painful and may cause immediate harm to your ears. The threshold for human hearing is typically zero (0) decibels, which is the quietest sound an average human can perceive under ideal conditions and decibel levels at 130 and above is at the threshold of pain and can rupture the tympanic membrane or eardrum. Hearing protection is recommended in environments with high noise levels to prevent long-term damage to the ears.

Sound	Intensity	Remarks
Normal Breathing	10 dB	A very quiet, almost inaudible sound, like gentle breathing.
Whispering	20 dB	Quiet conversation or a soft whisper
Library	30 dB	A quiet library environment where people speak in hushed tones.
Refrigerator	40 dB	The sound of a typical household refrigerator.
Rainfall	50 dB	The sound of moderate rainfall.
Normal Conversation	60 dB	Typical conversation levels.
Busy Street Traffic	70 dB	Noise from busy urban street traffic.
Vacuum Cleaner	80 dB	The sound produced by a vacuum cleaner.
Lawn Mower	90 dB	The noise emitted by a typical lawn mower.
Concert	100 dB	The loudness experienced during a rock concert or other live music events.
Jackhammer	110 dB	The noise generated by a jackhammer during construction.
Ambulance Siren	120 dB	The loud siren of an emergency vehicle.
Rock Concert (front seat)	120 -1 30 dB	The high decibel levels experienced in close proximity to loudspeakers at a rock concert.
Jet Engine (at takeoff)	140 dB	The intense noise produced by a jet engine during takeoff.
Fireworks	150 dB	The loud explosions and pops produced by fireworks.

Selected List of Sound Intensity Levels

Hearing Loss and Protection

The ear can be susceptible to damage and hearing loss due to factors such as prolonged exposure to loud noises, age-related changes, or certain medical conditions. Taking appropriate measures to protect the ears, such as using hearing protection devices and avoiding excessive noise exposure, is crucial for preserving hearing health.

Studying the structure and function of the human ear helps us appreciate the intricate mechanisms involved in sound perception. It allows us to recognize the importance of protecting our hearing and highlights the remarkable capabilities of the auditory system.

Advances in technology plays a significant role in helping us develop assistive listening devices to help correct hearing impairments. Technologies like hearing aids, cochlear implants, and personal amplification systems improve sound perception and communication for those with hearing loss, enhancing their quality of life.

SONAR: Sound Navigation and Ranging

Sound Navigation and Ranging or SONAR systems utilize sound waves to detect and locate objects underwater and help us better understand our underwater environment. The most common applications of SONAR include marine navigation, underwater exploration, fisheries, military operations and oceanographic research. SONAR operates on the principle of echo-ranging which involves emitting sound waves or pings into the water and measuring the time it takes for the sound waves to return (echo) after bouncing off an object. The system is comprised of a transducer that emits the sound waves into the water and receives the returning echoes, a hydrophone that detects and converts the acoustic echoes into electrical signals, a signal processor that filters and extracts useful information from the echoes and displays it in a meaningful format and a display unit that provide real-time displays of the underwater environment, such as depth profiles, object detection, and mapping.

SONAR systems can be active or passive. Active SONAR systems emit sound waves and analyzes the returning echoes. They provide detailed information about the range, bearing, and characteristics of underwater objects. Active SONAR is used in navigation, target detection, and imaging applications. Conversely, Passive SONAR systems listen for sounds emitted by underwater objects, such as marine mammals, submarines, or ships. By analyzing these sounds, passive SONAR can identify and locate the sources. Passive SONAR is commonly used for underwater surveillance, environmental monitoring, and marine mammal research.

Ultrasound

Ultrasonography or ultrasound imaging is based on the principle of sound wave propagation and reflection. Ultrasound uses high-frequency sound waves, typically above 20,000 Hz, which are beyond the range of human hearing to generate images of structures. Ultrasounds use a transducer to emit sound waves into a body. The transducer converts electrical energy into sound waves (transmission mode) and sound waves into electrical signals (reception mode). Whenever the sound waves encounter different tissues and structures within the body, the waves bounce back or reflects producing echoes. The echoes are then detected by the transducer and converted into electrical signals. These signals are processed and used to create real-time images or videos of the internal structures which are then displayed on a screen in the form of images or videos.

One of the most frequent uses of ultrasound is for visualizing and interpreting internal structures and organs in the human body. It has become an indispensable tool in medical diagnostics because it can provide valuable information without the need for invasive procedures. Ultrasonography has numerous applications in medical diagnostics and imaging. Some of the most common uses include:

a. Sonogram (Obstetrics) used to assesses the health, determines position and detects potential fetal abnormalities.
b. Abdominal (Internal organs) used to visualize and evaluate internal organs including the liver, gallbladder, pancreas, kidneys and spleen and assist in the diagnosis of conditions such as gallstones, tumors, and cysts.
c. Echocardiogram (Cardiology) used to visualize the heart and its structures. It aids in assessing heart function, identifying abnormalities and diagnosing cardiovascular diseases.
d. Musculoskeletal (Orthopedics) used to examine muscles, tendons, ligaments, and joints. It helps diagnose conditions such as sprains, tears, and inflammation. It is also used for guided injections and interventions.
e. Breast Imaging is used alongside mammography to evaluate breast abnormalities, such as cysts, tumors, or masses. It helps guide breast biopsies and assists in the early detection of breast cancer.

Though primarily used in human medicine, ultrasounds are also used in veterinary medicine, underwater exploration, seafloor mapping and marine research. The technology is also used in non-destructive testing (NDT) in manufacturing, aerospace industries and material science for detecting defects, measuring thickness and assessing structural integrity.

3D Prenatal Ultrasound Image (*credit:* Tiny Toes Prenatal Imaging©)

The Doppler Effect

In 1842, Austrian mathematician and physicist Christian Doppler (1803 - 1843) hypothesized that the observed frequency of a wave depends on the relative speed of the source and the observer. This phenomenon known as the Doppler Effect describes the change in frequency or wavelength of a wave as observed by a bystander at rest.

As previously discussed, sound waves are longitudinal so they move parallel from the source of disturbance through the medium. Because the source emits the sound waves at a constant frequency, the time between the peaks will be the same for each individual sound wave. Since the source continues to move while emitting the sound waves, the waves fronts are pushed together at the front of the moving body and spread further apart at the back.

This is quite noticeable when an emergency vehicle with sirens blaring passes you on the street. When the vehicle is approaching, the sound waves are pushed closer together in front of the moving vehicle which increases the frequency of the waves and results in a higher pitch. And as the vehicle passes and the source moves away from the observer, the waves stretch out in its wake resulting in a decrease in frequency and a lower pitch sound. This produces the familiar *whee-whoom* sound we associate with emergency vehicles.

The Doppler Effect is used in radar to measure the velocity and direction of moving objects, such as precipitation particles in the atmosphere. By analyzing the change in frequency of radio waves reflected from these objects, meteorologists can detect the presence of storms, determine wind patterns, and track weather systems. It is also utilized in astronomy to determine the motion and properties of celestial objects and in medical imaging to assess blood flow and evaluate blood circulation which can assist in detecting abnormalities such as blood clots and problems such as atherosclerotic blockages.

The Sonic Boom

The Doppler Effect contributes to another phenomenon in physics known as a **sonic boom**. When sound waves are produced by a moving source or object, the sound waves in front of the object are pushed closer together. Due to the Doppler Effect, if the object producing the sound waves is moving faster than the speed of sound, the frequency of the waves increase causing the sound waves in front of the object to overlap and bundle up or become compressed. This in turn causes a sudden increase in pressure and generates a shock wave known as a sonic boom. The compression and rarefaction of waves behind the source lead to the characteristic "boom" sound.

Sound Systems and Entertainment

Sound systems are play a central role in various forms of entertainment, including live performances, cinemas, home theaters and public address systems. Sound engineers and technicians utilize advanced audio equipment and techniques to amplify and distribute sound effectively to provide optimal listening experiences for audiences. Surround sound technology enhances immersion in movies and gaming, creating a more immersive and engaging experience.

To provide sound experiences such as surround sound, engineers process the sound waves and extract valuable information from audio signals. They utilize a series of advanced techniques such as spectral analysis, Fourier transforms and digital signal processing to analyze sound waves and extract characteristics such as frequency content, harmonics, and noise. These applications are very useful in music production, speech recognition, acoustic measurements, and audio forensics.

Sound and Technology

The ability to record sound has revolutionized how we capture and preserve audio information. It allows us to create digital recording systems and the ability to document music, speeches, conversations and other audio content for playback and analysis. It also allows us to enjoy recorded sound through devices such as speakers and headphones. Overall sound is critical to various aspects of technology and communication continue to advance and shape the way we interact with the world.

Understanding the physics of sound is imperative to architects and engineers who use acoustic principles such as soundproofing and sound reflecting surfaces to control and shape sound within buildings, concert halls, theaters, and other environments and create spaces with optimal sound quality and minimal unwanted noise.

Sound is an essential component of telecommunications, enabling effective communication across vast distances. Technologies such as telephones, mobile phones, and Voice over Internet Protocol (VoIP) systems rely on sound transmission to facilitate real-time conversations. It is also what enable us to use voice recognition systems and do audio and video conferencing collaboratively and seamlessly.

Sound technology continues to advance rapidly, enabling us to communicate, entertain, and interact with the world in new and innovative ways. By harnessing the power of sound, scientists and engineers drive advancements in various fields, enhancing our ability to capture, reproduce, analyze, and utilize audio information.

Conclusion

Though all waves are very important, sound waves, in particular, have a profound impact on our lives. Sound enables us to communicate, perceive our environment, enjoy music and experience the world around us. The ear is a remarkable organ that converts mechanical vibrations into electrical signals that the brain can process allows us and other living things to detect and interpret sound,

Moreover, sound technology has revolutionized various fields, including telecommunications, entertainment, medical diagnostics, and underwater exploration. Technologies like SONAR and ultrasound utilize sound waves to gather information, create images, and facilitate communication in different contexts. They contribute to advancements in fields such as marine navigation, medical imaging, and scientific research.

Furthermore, the relationship between sound and music is deeply intertwined. Music is a form of organized sound that expresses emotions, communicates ideas, and connects individuals on a cultural and personal level. Sound elements, such as pitch, timbre, and rhythm, are manipulated to create melodies, harmonies, and rhythms that form the essence of musical compositions.

In summary, the study of waves, sound, and their applications enriches our understanding of the world, enhances communication and technology, and allows us to express our creativity and emotions through music. Exploring the intricacies of waves and sound opens doors to scientific discoveries, technological innovations, and artistic endeavors, shaping the way we perceive and interact with our surroundings.

Problems

1. Sound travels at a velocity of 343 m/s in dry air. If an animal emits a 550Hz sound, what will be the wavelength of the soundwave?
2. If a peal of thunder is heard 12 seconds after seeing the flash the lightning, how far away is the thunderstorm?
3. A car is moving at a speed of 30 m/s toward a stationary observer. If the frequency of the car's horn is 400 Hz and the speed of sound is 340 m/s, calculate the frequency heard by the observer.
4. A sound wave traveling in air strikes a wall and reflects. If the distance to the wall is 10 meters and the time for the echo to return is 0.1 seconds, calculate the speed of sound in air.
5. What is rarefaction?
6. What is the difference between intensity and loudness?
7. What is the doppler effect?
8. What causes beats in music?