Chapter 6: Wave Motion and Sound

At the end of the lesson, students should be able to:

- Define waves and wave motion
- Define amplitude, period and frequency of a period signal
- Understand transverse and longitudinal waves
- Understand wave interferences
- Explain the nature of sound
- Explain pitch, intensity and quality of sound using wave theory
- Describe how sounds travel through different mediums
- Understand electromagnetic wave applications in autonomous vehicle: ultrasonic and radar.
- Explain the Doppler Effect and its application
- Understand telemetry in an autonomous electric car
- Introduction to Signal Frequency Domains

6.1 Introduction to wave and wave motion

A wave is a disturbance that travels through a medium from one location to another location. The wave medium is the substance that carries a wave (or disturbance) from one location to another. The wave medium is not the wave and it does not make the wave; it merely carries or transports the wave from its source to other locations. For example, space could be the medium that transfer the wave energy and momentum. Note that wave of electromagnetic radiation can travel through vacuum, that is, without a medium.

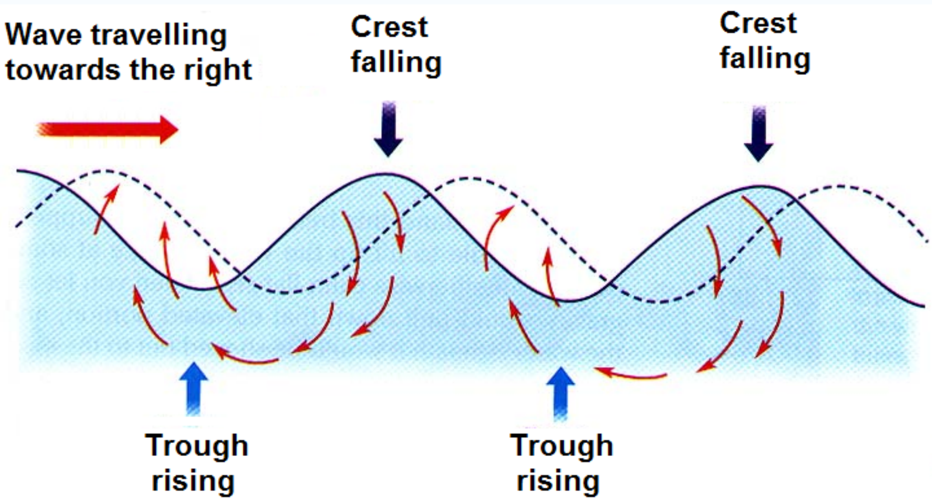


Figure 6.1: Wave motion of water

Note that you can be carried up and forward when the water wave approaches and down and backward when the wave goes down. This clearly shows energy is involved in wave motion.

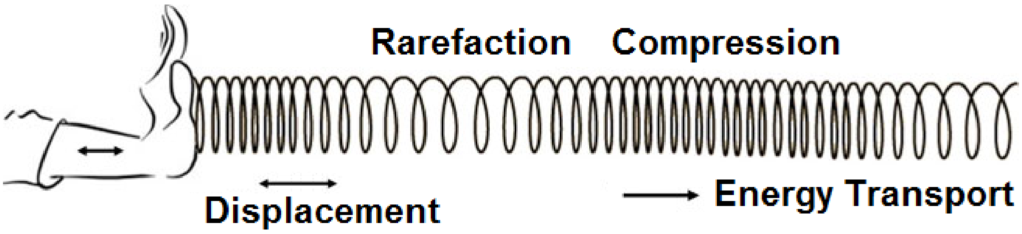


Figure 6.2: Wave motion in a slinky coil

Waves creates an **energy transport phenomenon**. As a disturbance moves through a medium from one particle to its adjacent particle, energy is being transported from one end of the medium to the other. In a slinky wave, a person imparts energy to the first coil by doing work upon it. The first coil receives a large amount of energy that it subsequently transfers to the second coil. When the first coil returns to its original position, it possesses the same amount of energy as it had before it was displaced. The first coil transferred its energy to the second coil. The second coil then has a large amount of energy that it subsequently transfers to the third coil. When the second coil returns to its original position, it possesses the same amount of energy as it had before it was displaced. The third coil has received the energy of the second coil. This process of energy transfer continues as each coil interacts with its neighbor. In this manner, energy is transported from one end of the slinky to the other, from its source to another location.

Wave transport energy and not the matter in the medium. When a wave is present in a medium (that is, when there is a disturbance moving through a medium), the individual particles of the medium are only temporarily displaced from their rest position. There is always a force acting upon the particles that restores them to their original position.

The particles of the medium water molecules or slinky coil simply vibrate about a fixed position as the pattern of the disturbance moves from one location to another location. In a water wave, each molecule of the water ultimately returns to its original position. In a slinky wave, each coil of the slinky ultimately returns to its original position.

Periodic waves are characterized by *crests* (highs) and *troughs* (lows).

Examples of waves include:

- Ocean surface waves, which are perturbations that propagate through water.
- Radio waves, microwaves, infrared rays, visible light, ultraviolet rays, x-rays, and gamma rays make up electromagnetic radiation. In this case, propagation is possible without a medium, through vacuum.
- Sound — a mechanical wave that propagates through air, liquid or solids.
- Seismic waves in earthquakes.

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

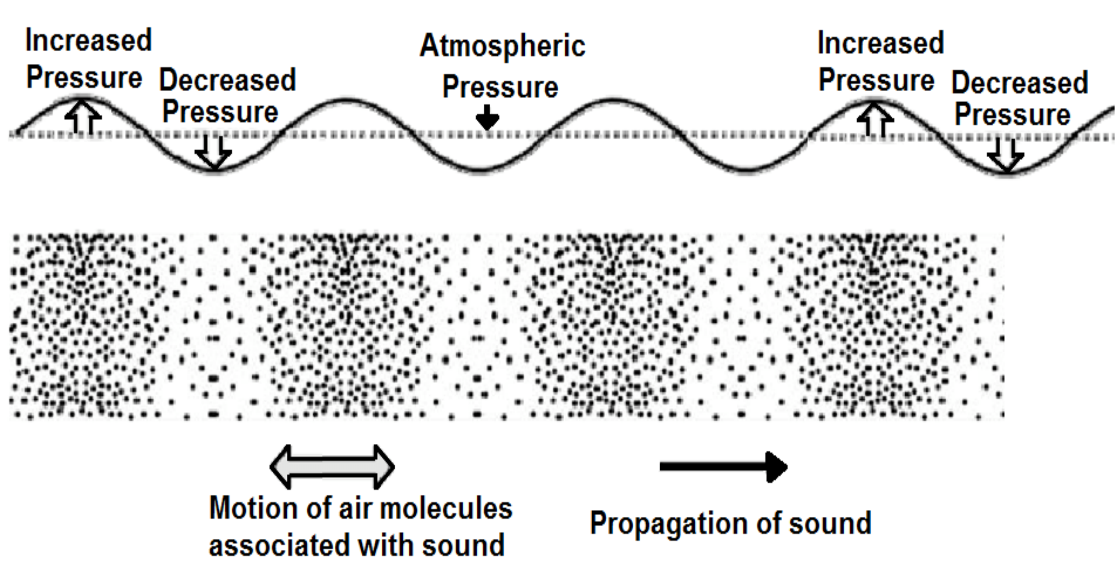
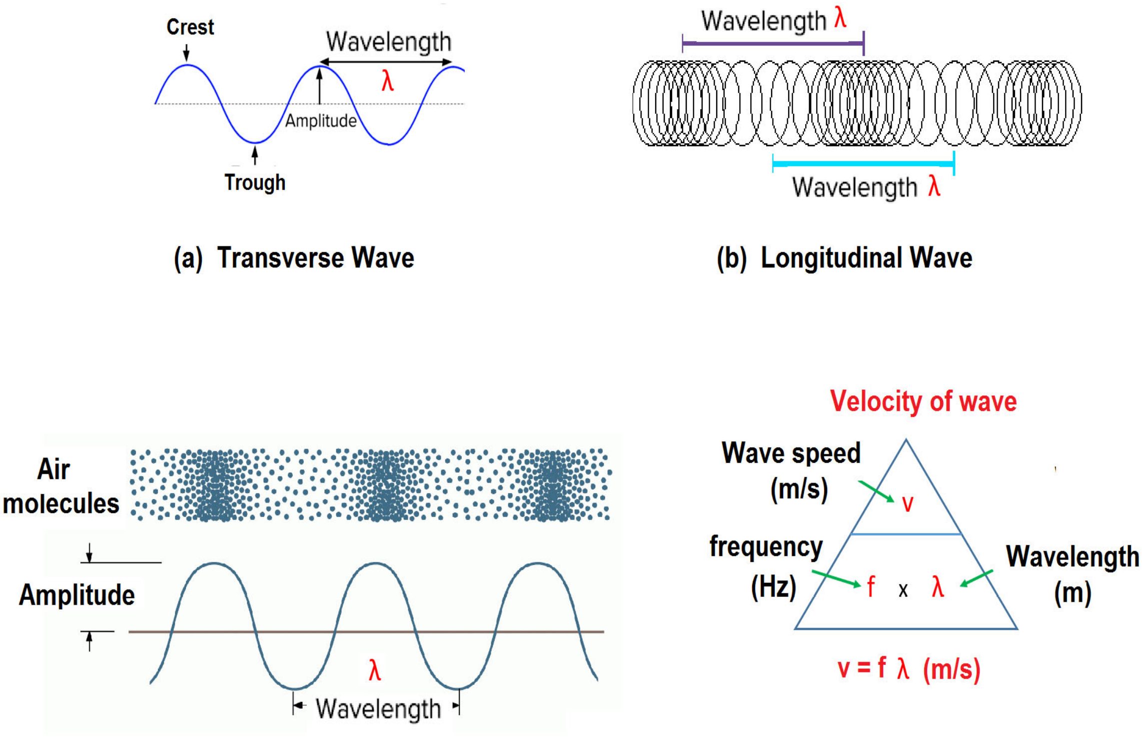


Figure 6.3: Wave motion in a sound

6.2 Amplitude, velocity, wavelength, period and frequency of a wave



(a) Transverse Wave

(b) Longitudinal Wave

(c) Sound Wave

(d) Velocity of Wave

Figure 6.4: Transverse, Longitudinal and Sound waves

Example 6.1

The velocity of sound in seawater is 1531 m/s. Find the wavelength in seawater of a sound wave whose frequency is 256 Hz.

$$v = f\lambda \ \text{(m/s)}$$

$$\lambda = \frac{1531}{256}$$

$$= 5.98 \text{ m}$$

Example 6.2

An anchored boat is observed to rise and fall through a total range of 2m once every 4s as waves whose crests are 30 m apart pass by it. Find (a) the amplitude (b) the frequency of the waves and (c) the velocity of the wave.

(a) Amplitude is 1 m.
(b) Period is 4 s; hence, frequency is ¼ = 0.25 Hz
(c)

$$v = f\,\lambda \ \ (m/s)$$
$$= 0.25 \times 30$$
$$= 7.5 \text{ m/s}$$

6.3 Transverse and longitudinal waves

You have been introduced to transverse and longitudinal waves in section 6.2. It was shown than pperiodic waves can be categorized as either longitudinal or transverse.

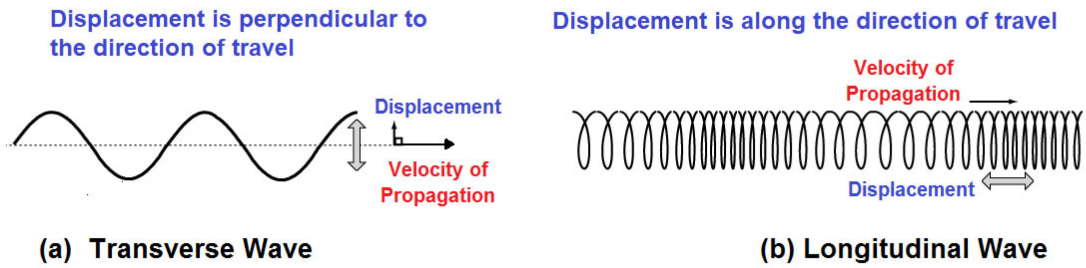


Figure 6.5: Transverse and Longitudinal Waveforms

For transverse waves, the displacement of the medium is perpendicular to the direction of propagation of the wave. A ripple on a pond, a wave on a string and electromagnetic waves are examples of transverse waves.

In longitudinal waves, the displacement of the medium is parallel to the propagation of the wave. A wave in a "slinky" is a good visualization. Sound waves in air are longitudinal waves. There is compression and rarefaction of as the longitudinal wave travels.

6.4 Wave interferences and Stationary wave

Interference is the addition (superposition) of two or more waves that result in a new wave pattern.

The principle of superposition of waves states that the resultant displacement at a point is equal to the sum of the displacements of different waves at that point. If a crest of a wave meets a crest of another wave at the same point then the crests interfere *constructively* and the resultant wave amplitude is greater. If a crest of a wave meets a trough of another wave then they interfere *destructively*, and the overall amplitude is decreased.

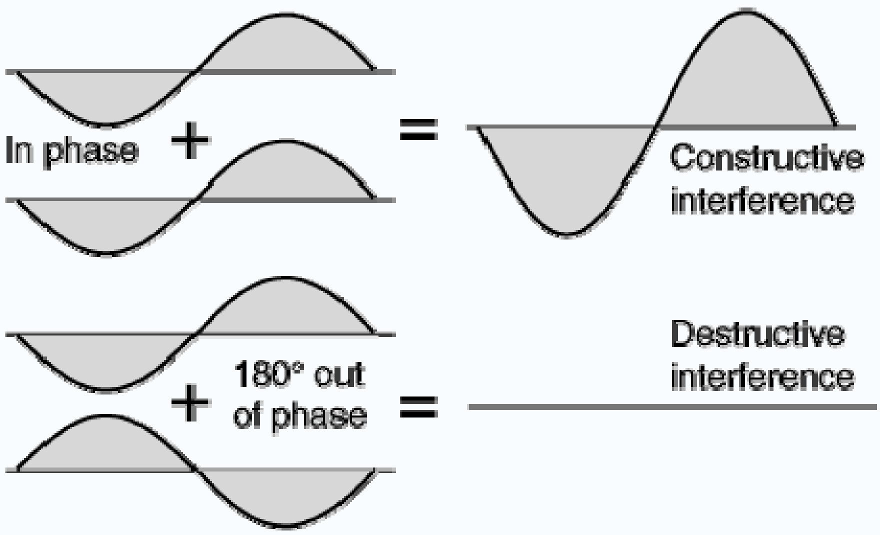


Figure 6.6: Interference of waves

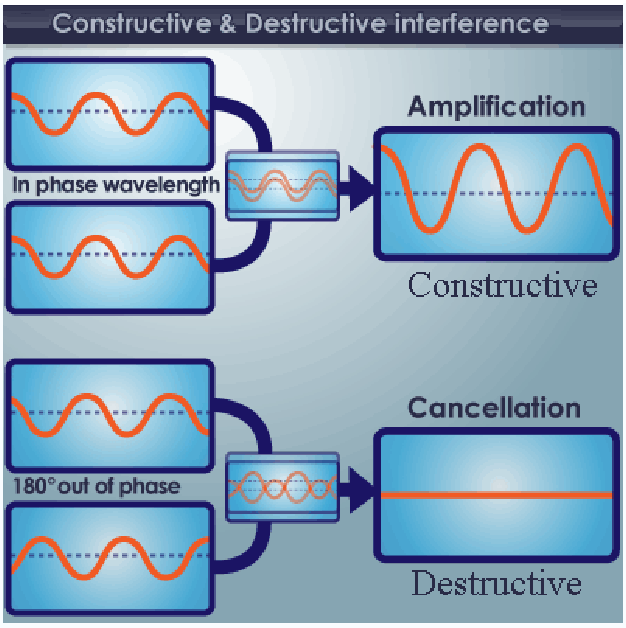


Figure 6.6: Interference of waves

Standing wave, also called stationary wave, is a combination of two waves moving in opposite directions, each having the same amplitude and frequency. The waves are superimposed resulting in their energies either added together or cancelled out. All standing wave patterns consist of nodes and antinodes. The points where displacement is zero are called nodes and the points where the displacement is maximum are called antinodes. Pressure changes are maximum at nodes and minimum at antinodes. All the particles except those at the nodes, execute simple harmonic motions of same period.

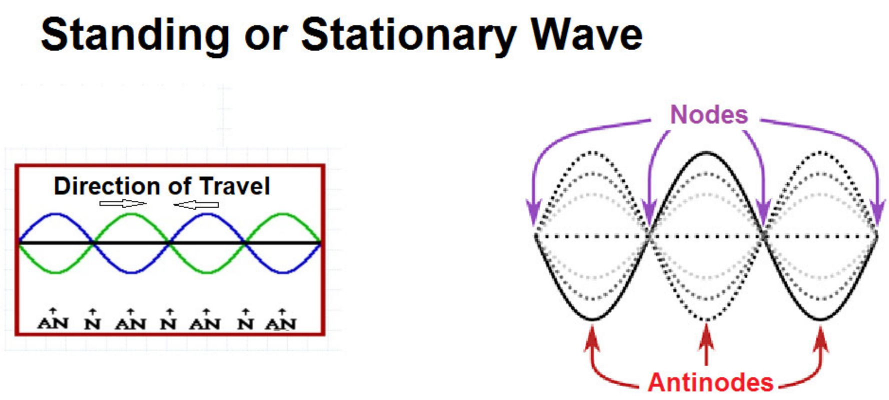


Figure 6.7: Concepts of a Standing or Stationary Wave

https://www.youtube.com/watch?v=CAe3lkYNKt8

6.5 The nature of sound

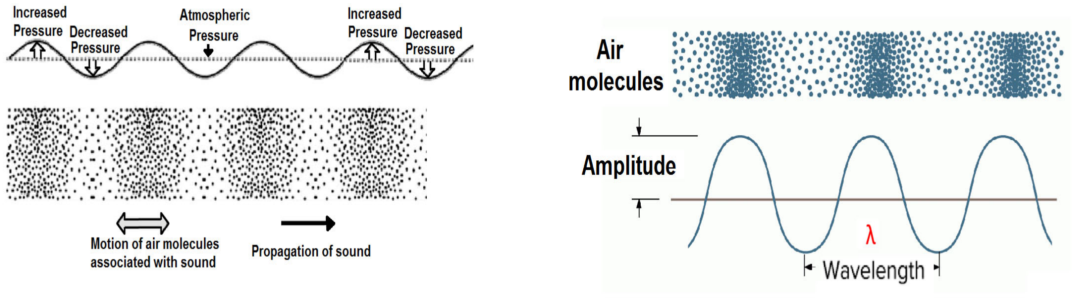
Sound is a disturbance of mechanical energy that propagates through matter as a wave. Sound is characterized by the properties of waves, which are frequency, wavelength, period, amplitude, pitch, intensity, quality and speed.

Humans perceive sound by the sense of hearing. By sound, we commonly mean the vibrations that travel through air and are audible to people. However, scientists and engineers use a wider definition of sound that includes low and high frequency vibrations in air that cannot be heard by humans, and vibrations that travel through all forms of matter, gases, liquids, and solids.

The matter that supports the sound is called the medium. Sound propagates as waves of alternating pressure, causing local regions of compression and rarefaction. Particles in the medium are displaced by the wave and oscillate. The scientific study of sound is called acoustics.

Humans can generally hear sounds with frequencies between 20 Hz and 20 kHz (the audio range) although this range varies significantly with age, occupational hearing damage, and gender; the majority of people can no longer hear 20,000 Hz by the time they are teenagers, and progressively lose the ability to hear higher frequencies as they get older. Most human speech communication takes place between 200 and 8,000 Hz and the human ear is most sensitive to frequencies around 1000-3,500 Hz. Sound above the hearing range is known as ultrasound, and that below the hearing range as infrasound.

A single-frequency sound wave traveling through air will cause a sinusoidal pressure variation in the air. The air motion that accompanies the passage of the sound wave will be back and forth in the direction of the propagation of the sound, a characteristic of longitudinal waves.



(a) (b)

Figure 6.8: Wave motion produced by a sound travelling through air

6.6 Loudness, Intensity, Pitch and quality of sound

In the earlier section, we have understand that sounds have amplitude, period, frequency, wavelength and speed. Sounds can also generally characterized by pitch, loudness, intensity and quality.

6.6.1 Loudness of sound

Sound loudness is a subjective term describing the strength of the ear's perception of a sound. The loudness a sound increases with its amplitude.

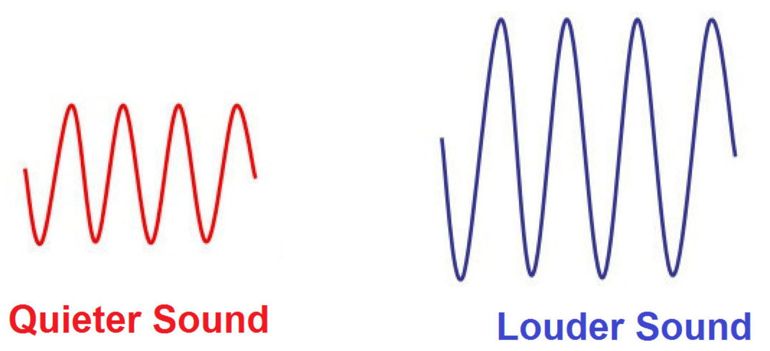


Figure 6.9: Loudness of a sound

6.6.2 Intensity of sound

Loudness of sound is intimately related to sound intensity but can by no means be considered identical to intensity. Hence, loudness is not simply sound intensity! A general "rule of thumb" for loudness is that the power must be increased by about a factor of ten to sound twice as loud.

The loudness of a sound is much more closely related to the logarithm of the intensity. Sound level is measured in decibels (dB) and is defined as:

$$\text{Loudness } \beta \text{ (in dB)} = 10 \log_{10} \frac{I}{I_o}$$

Where I is the intensity of sound and $I_O = 10^{-12}$ W / m^2

Approximate sound levels and intensities within human hearing range

Source of sound	Intensity level (dB)	Intensity ($W\ m^{-2}$)	Perception
jet plane at 30 m	140	100	extreme pain
threshold of pain	125	3	pain
pneumatic drill	110	10^{-1}	very loud
siren at 30 m	100	10^{-2}	
loud car horn	90	10^{-3}	loud
door slamming	80	10^{-4}	
busy street traffic	70	10^{-5}	noisy
normal conversation	60	10^{-6}	moderate
quiet radio	40	10^{-8}	quiet
quiet room	20	10^{-10}	very quiet
rustle of leaves	10	10^{-11}	
threshold of hearing	0	10^{-12}	

Table 6.1 : Sound intensity and its effect on human ears

6.6.3 Pitch of sound

The perceived pitch of a sound is just the ear's response to frequency, i.e., for most practical purposes the pitch is just the frequency. The higher the frequency, the higher is the pitch.

The pitch of a string instrument can be changed by changing the length of the string, by changing the tension of the string or by using thinner or thicker string.

$$\text{frequency, } f = \frac{1}{\text{Period}} \text{ (Hertz)}$$

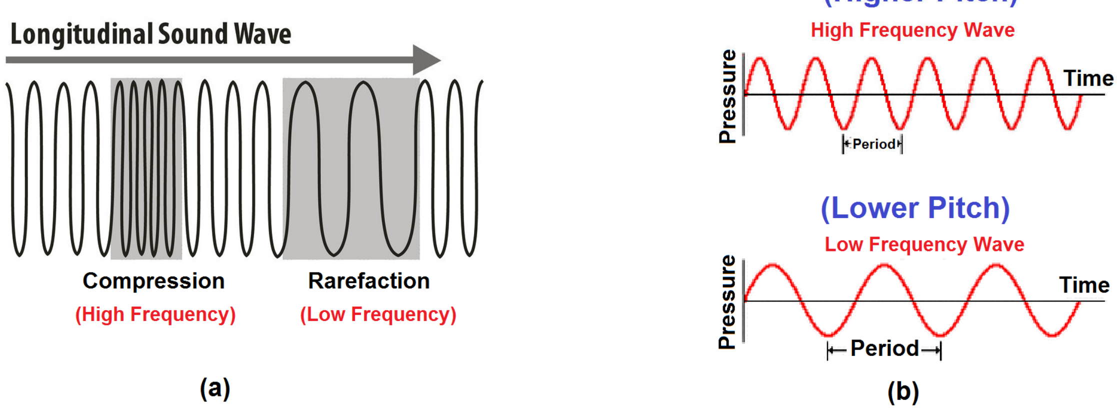


Figure 6.10: Wave motion produced by a sound travelling through air

6.6.4 Quality of sound

Sound "quality" or "timbre" describes those characteristics of sound that allow the ear to distinguish a particular musical note sound different from another, even when they have the same pitch and loudness. Thus, timbre is then a general term for the distinguishable characteristics of a tone.

Timbre is what makes sound quality measures the worth of an audio recording. Sound quality can also be a measurement of sound accuracy, especially when considering the value of a digital sound. Sound quality can be a measurement of how accurate a digital system produces an original sound wave.

Thought there are measurement of the value of sound, it is really up to the listener's opinion whether a sound has good quality or not.

Sound quality can be affected by a number of elements, and these can be applied during anytime of producing the sound, for instance faults in equipment could occur during the recording stages, or quality can be reduced by which file formats are used when storing digital sounds.

Also sound quality is determined by the compression method used to store the files, for instance it depends on the number of audio channels open, i.e. mono, stereo, multi-channel, etc.

6.7 Speed of sound travelling through different media

The propagation speeds of traveling sound waves are characteristic of the media in which they travel and are generally not dependent upon the other wave characteristics such as frequency, period, and amplitude. The speed of sound in dry air is given approximately by

$$\textbf{Speed of sound in air, } V \approx 331.4 + 0.6T_C \quad \text{(m/s)}$$

where T_C is the temperature of the air in Celcius

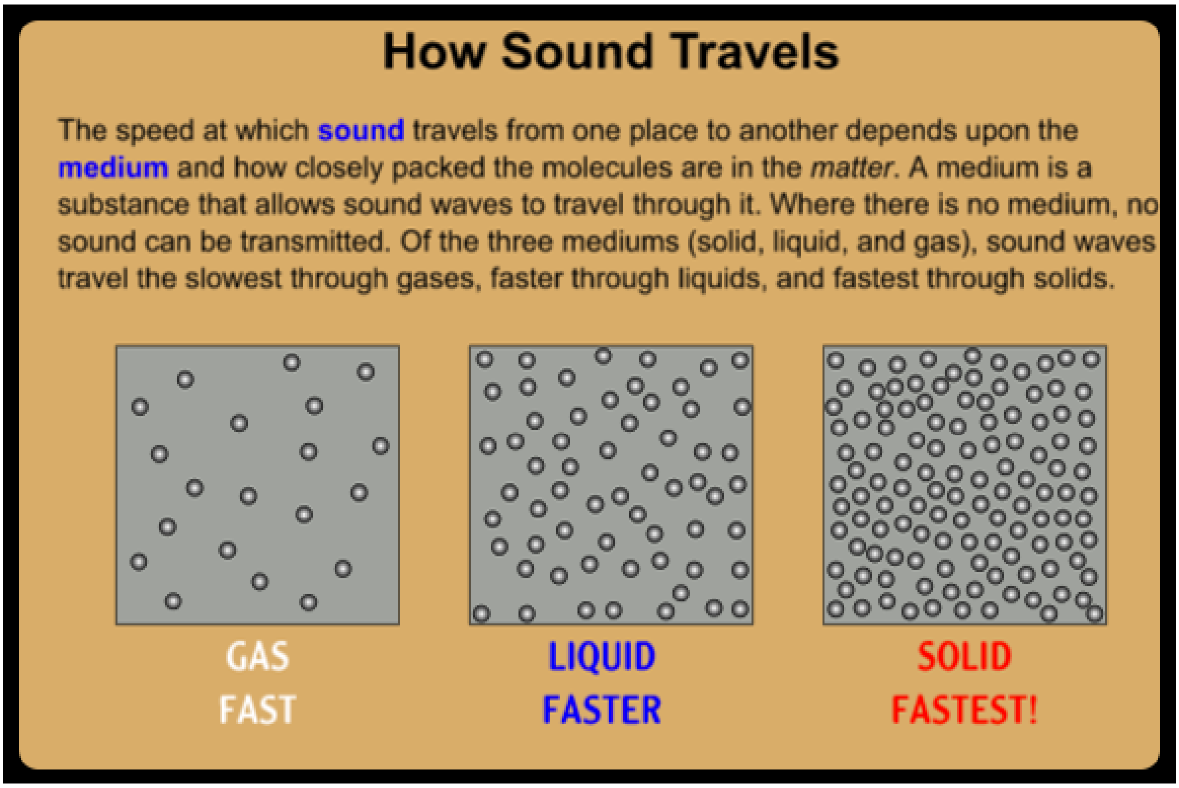


Figure 6.11: How sound travels through different medium

The speed of sound is dependent on the type of medium and the temperature.

The speed of sound in air and other gases, liquids, and solids can be calculated from their density and elastic properties of the medium (bulk modulus). The wave speed takes the general form

Y is Young's Modulus

B is Bulk Modulus

P is the density of medium

$$v = \sqrt{\frac{B}{P}}$$

Speed of sound in Liquid or Gas

$$v = \sqrt{\frac{Y}{P}}$$

Speed of sound in Solid

State	Substance	Speed in m/s
Solids	Aluminium	6420
	Nickel	6040
	Steel	5960
	Iron	5950
	Brass	4700
	Glass (Flint)	3980
Liquids	Water (Sea)	1531
	Water (distilled)	1498
	Ethanol	1207
	Methanol	1103
Gases	Hydrogen	1284
	Helium	965
	Air	346
	Oxygen	316
	Sulphur dioxide	213

Table 6.2: Speed of sound in various medium

Example 6.3

What is the approximate speed of sound in air at room temperature of 20^0 C?

Using,

$$\textbf{Speed of sound in air, V} \;\tilde{\approx}\; 331.4 + 0.6T_C \quad (m/s)$$

Speed of sound in air at 20^0 C = 331.4 + 0.6 (20) = 343.4 m/s (approximately).

Example 6.4

Compute the speed of sound in an aluminium rod. Young's modulus and density for aluminium are:

Y = 6.89 x 10^7 N/m^2 ρ = 2.7 kg / m^3. `

Using

$$v = \sqrt{\frac{Y}{P}} = \sqrt{\frac{6.89 \times 10^7}{2.7}} = 5052 \text{ m/s}$$

6.8 Ultrasonic principle and application

The term "**ultrasonic**" applied to **frequencies** higher than those of audible sound and is nominally over 20,000 hertz. Thus, ultrasonic sound frequencies are above the range of human hearing.

Frequencies used for medical diagnostic **ultrasound** scans may extend to 10 MHz and beyond. Ultrasonic sound frequencies are above the range of human hearing.

There are ultrasonic sensors in autonomous vehicles to help them to navigate safely. These ultrasonic sensor works on the principle of emitting high frequency sound pulses and detecting or measuring their return after being reflected to determine the distance to an object.

In short, ultrasonic sensors are used to detect objects and measure distances between the object and the moving car to ensure safe maneuvering.

Ultrasound imaging or sonography is also often used in medicine. In the non-destructive testing of products and structures, ultrasound is used to detect invisible flaws.

Referring to Figure 6.12, the transducer is a transceiver. A transceiver is radio unit that can transmit and receive a return signal. It transmit a sound wave outward at a particular frequency and wait for the sound to be echoed back. If there is no object blocking the path of the transmitted ultrasound signals, there will be no return echo. When there is an object blocking the sound path, the ultrasonic sound is reflected back as echoes to the transducer. Since the velocity (in m/s) and the time taken (in seconds) for the signal to be sent and received are known, the object distance can be quickly calculated by the computer.

The distance, s, of the object from the autonomous car using ultrasonic sensor is given by:

$$s = \frac{\text{velocity of sound} \times \text{time taken for the signal to be emitted and returned}}{2} \quad \text{(m)}$$

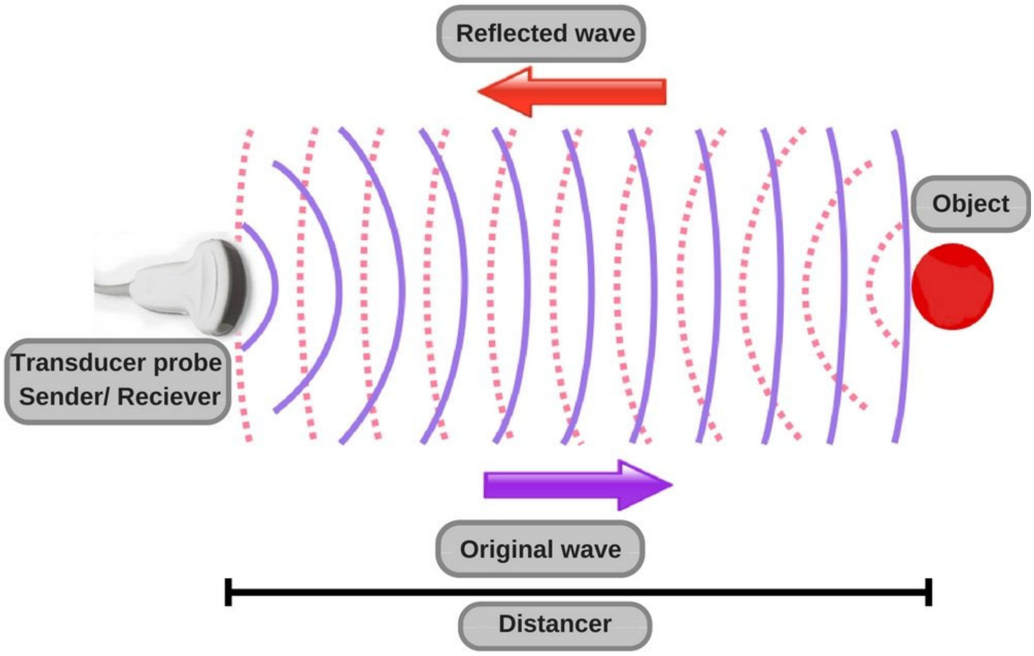


Figure 6.12: Working concept of ultrasonic sound in detecting an object

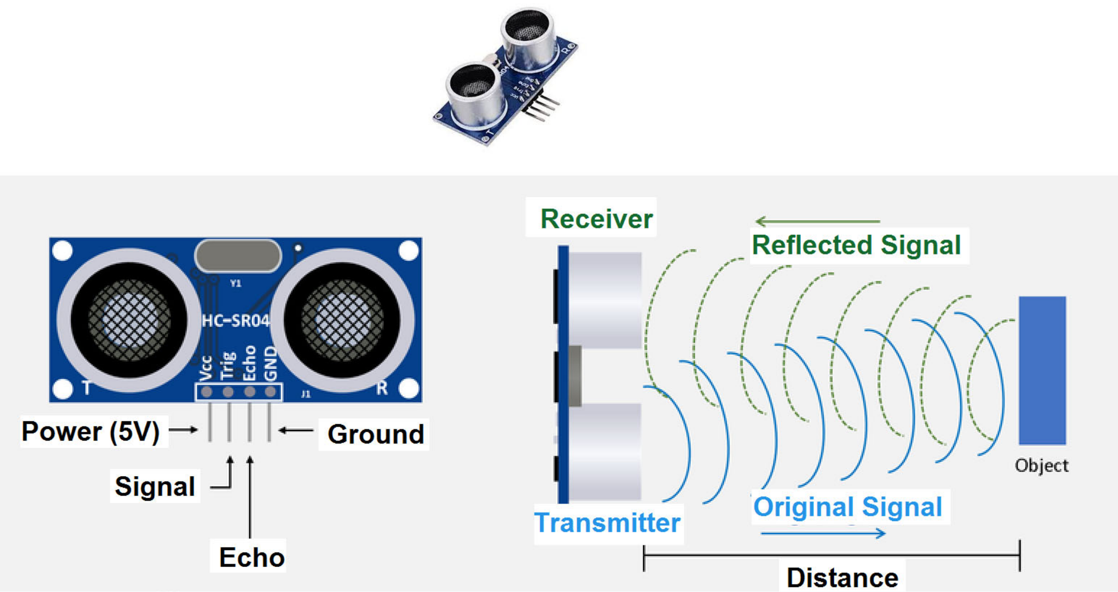


Figure 6.13: Working concept of ultrasonic sound in detecting an object

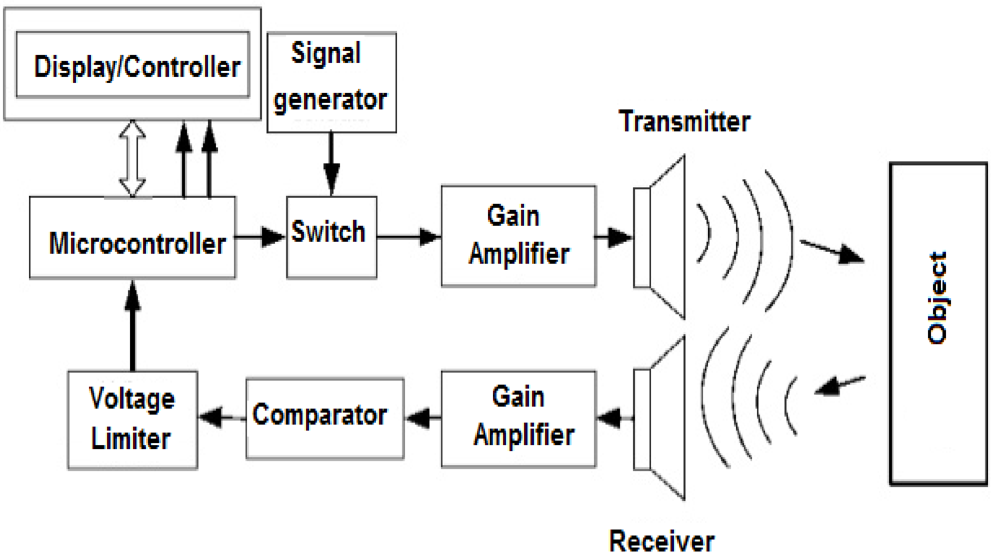


Figure 6.14: Ultrasonic sensors concept

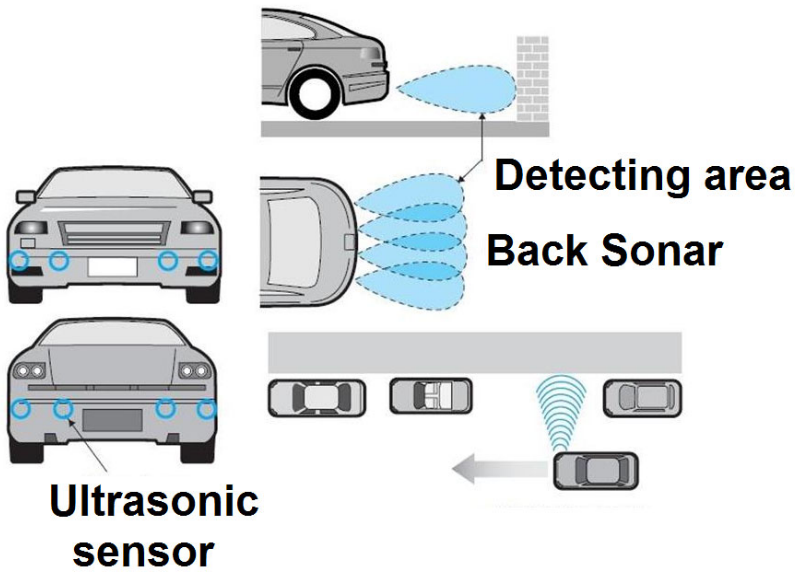


Figure 6.15: Ultrasonic sensors application on an autonomous car

https://www.youtube.com/watch?v=T11ptR8ICl4 (How does an ultrasonic sensor work?)
https://www.youtube.com/watch?v=vf2IW4LkmMQ (Ultrasonic sensor working principle)

6.8.1 Radar principle and applications

Radar is an acronym for "radio detection and ranging." A radar system usually operates in the ultra-high-frequency (**UHF**) or microwave part of the radio frequency **(RF)** spectrum, and is used to detect the position and/or movement of objects. Radar travels at the speed of light at $3X10^8$ m/s. Radar is simply a method of using radio waves to determine the range, angle and relative velocity of objects.

The concept of using radar for finding the distance of an object is very similar to the ultrasonic sensor except for the speed of radar is faster at $3X10^8$ m/s. The radar unit is also a transceiver. It sends pulses of radar signal and wait for the returning echoes when an object blocks the signals.

The distance, s, of the object from the radar is given by

$$s = \frac{3 \times 10^{8} \times \text{time taken for the signal to be emitted and returned}}{2} \quad \text{(m)}$$

6.8.2 Doppler Effect and its applications

Radar can also be used to measure the speed of an object using a phenomenon called **Doppler shift**. Like sound waves, radar sends out a certain **frequency** when in used. There are three scenarios.

6.8.2a The object is stationary

When the radar and the object are both standing still, the echo will have the same wave frequency as the original transmitted frequency.

6.8.2b The object is moving away from the radar

When the object is moving, each part of the radar signal is reflected at a different point in space, which changes the wave pattern. When the object is **moving away** from the radar, the second segment of the sine wave has to travel a greater distance to reach the object than the first segment of the signal. This has the effect of "stretching out" the wave, or **lowering its frequency**. It takes a longer time for the next wave to reach the ear or receiver to hear/receive the next signal.

6.8.2c The object is moving towards the radar

If the object is moving **toward** the radar, the second segment of the wave travels a shorter distance than the first segment before being reflected. As a result, the peaks and valleys of the wave are squeezed together: This has the effect of "compressing" the wave, or **increasing its frequency**. It takes a shorter time for the next wave to reach the ear or receiver to hear/receive the next signal.

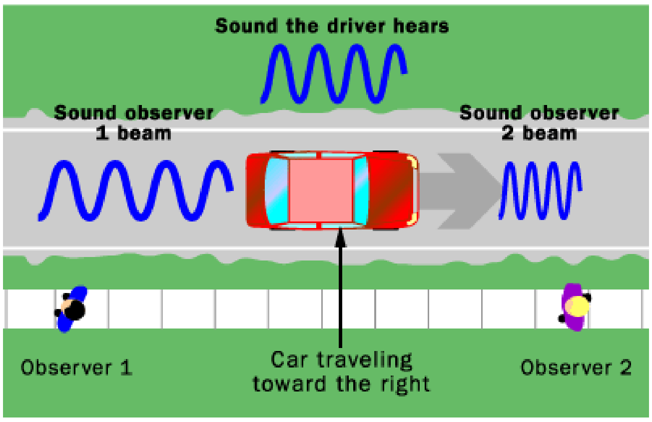


Figure 6.16: Doppler Effect or Shift

If the **car** is moving toward the **radar** device, the return signal has a shorter distance to travel and the radio wave frequency increases. The **radar** device can then use the change in frequency to determine the speed at which the **car** is moving. In laser-speed guns, waves of light are used in place of radio waves.

Doppler shift: Observer 1 hears a lower tone than the driver does because the car is moving away. Observer 2 hears a higher tone than the driver does because the car is approaching.

Based on how much the frequency changes, a radar gun can calculate how quickly a car is moving toward it or away from it. If the radar gun is used inside a moving police car, its own movement must also be factored in. For example, if the police car is going 50 miles per hour and the gun detects that the target is moving away at 20 miles per hour, the target must be driving at 70 miles per hour. If the radar gun determines that, the target is not moving toward or away from the police car, than the target is driving at exactly 50 miles per hour.

Radar guns have a cone or dish-shaped antenna that concentrates the radio signal, but the electromagnetic wave quickly spreads out over a wide area. The radar gun is configured so that it only monitors a particular target, not everything in the vicinity so chances are a detector will pick up the radio signal well before the radar gun recognizes the car.

- The radar transmits a short, powerful and high-intensity burst of high frequency radio waves for a microsecond.
- The transmitter is turned off
- The receiver is turned on to listen for an echo that is usually much weaker.
- The time taken for the echo to return is measured, as well as the Doppler shift of the echo.
- Since radio waves travel at the speed of light and if the radar has a good high-speed clock, it can measure the distance of the cars and stationary objects very accurately.
- Using special signal processing equipment, the radar set can also measure the Doppler shift very accurately and determine the speed of the incoming car.

6.9 Introduction to Signal Frequency domain

In electronics, control systems engineering, and statistics, the **frequency domain** refers to the analysis of mathematical functions or **signals** with respect to **frequency**, rather than time. The "spectrum" of **frequency** components is the **frequency-domain** representation of the **signal**.

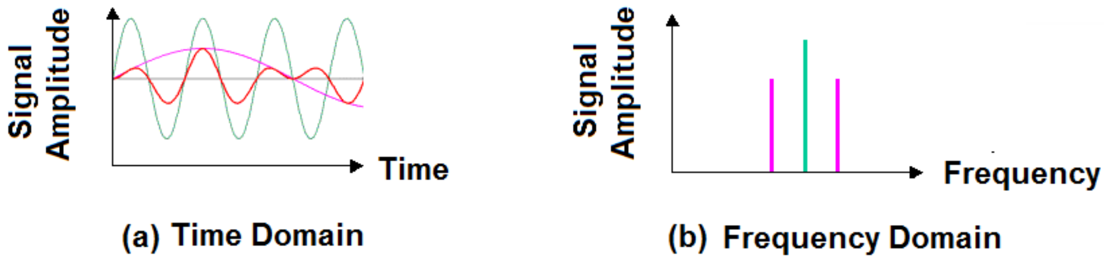


Figure 6.17: Time Domain versus Frequency Domain of a signal

Frequency domain analysis is mostly used to signals or functions that are periodic over time. This does not mean that **frequency domain** analysis cannot be used in signals that are not periodic. The most **important** concept in the **frequency domain** analysis is the transformation.

https://www.youtube.com/watch?v=YS6jaqeXVok (Introduction to Frequency Domain of Signals)
https://www.youtube.com/watch?v=B3u57yF2JSc (Frequency domain – tutorial 1: concept of frequency)

(Please watch the video)