A WRITE-UP

On the

PROPAGATION OF SOUND,
ITS TRAVEL PATH, TRAVEL MEDIUMS AND BEHAVIOR IN THE MEDIUMS.

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CHAPTER ONE
SOUND AND ITS PROPERTIES

1.0 INTRODUCTION

What is Sound?

Sound is a disturbance of the atmosphere that human beings can hear. Disturbances produced by practically everything that moves, especially if it moves quickly or in a rapid and repetitive manner.

Sound waves:

A wave is an oscillating disturbance that travels through a medium. Many forms of energy, including sound, travel in the form of waves. Sound waves are longitudinal waves originating from a source and conveyed through a medium (gaseous, liquid or solid).

When particles in the medium vibrate parallel to the direction the sound wave is traveling, we have a longitudinal wave. This is the type of sound wave produced by our transducers and used for medical diagnosis. In some materials, it is possible to transmit transverse waves, characterized by having the vibrations moving perpendicular (transverse) to the direction of wave travel. Transverse waves travel horizontally (from left to right) - the vibration direction is perpendicular (at right angles) to the direction in which the wave travels or propagates. Waves in water and on strings are two good examples.

1.1 PROPERTIES OF SOUND

1.1.1 Speed of Sound

The speed of sound is a term used to describe the speed of sound waves passing through an elastic medium. The speed varies with the medium employed (for example, sound waves move faster through water than through air), as well as with the properties of the medium, especially temperature.

The speed varies depending on atmospheric conditions; the most important factor is the temperature. Air pressure has almost no effect on sound speed. Air pressure has no effect at all.
in an ideal gas approximation, because pressure and density both contribute to sound velocity equally, and in an ideal gas the two effects cancel out, leaving only the effect of temperature. Sound usually travels more slowly with greater altitude, due to reduced temperature. Humidity has a small, but measurable effect on sound speed. Sound travels slightly (0.1%-0.6%) faster in humid air. The approximate speed of sound in 0% humidity (dry) air, in meters per second (m·s⁻¹), at temperatures near 0 °C, can be calculated from:

\[ c_{\text{air}} = 331.3 + (0.6 \cdot \varphi) \text{ m} \cdot \text{s}^{-1} \]

In general, solids will have a higher speed of sound than liquids, and liquids will have a higher speed of sound than gases.

In general, the speed of sound \( c \) is given by

\[ c = \sqrt{\frac{C'}{\rho}} \]

Where: \( C \) is a coefficient of stiffness
\( \rho \) is the density

Thus, the speed of sound increases with the stiffness of the material, and decreases with the density.

1.1.1.1 Speed of sound in solids

In a solid, there is a non-zero stiffness both for volumetric and shear deformations. Hence, in a solid it is possible to generate sound waves with different velocities dependent on the deformation mode.

In a solid rod (with thickness much smaller than the wavelength), the speed of sound is given by:

\[ c_{\text{solid}} = \sqrt{\frac{E}{\rho}} \]

Where: \( E \) is Young’s modulus
\( \rho \) (rho) is density

Thus, in steel the speed of sound is approximately 5100 m·s⁻¹.

1.1.1.2 Speed of sound in a Fluid

In a fluid the only non-zero stiffness is to volumetric deformation, (a fluid does not sustain shear forces).

Hence, the speed of sound in a fluid is given by

\[ c_{\text{fluid}} = \sqrt{\frac{K}{\rho}} \]

Where: \( K \) is the adiabatic bulk modulus
The speed of sound in water is of interest to those using acoustics as a tool in the oceans or lakes, e.g., for communication, mapping the ocean floor, or ocean acoustic tomography. In fresh water, sound travels at about 1435 m/s. In salt water, sound travels at about 1500 m/s. The speed of sound in seawater depends on pressure (hence depth), temperature (a change of 1 °C ~ 4 m/s), and salinity (a change of 1‰ ~ 1 m/s), and empirical equations have been derived to accurately calculate sound speed from these variables.

1.1.1.3 Speed of sound in ideal gases and in air

For a gas, \( K \) (the bulk modulus in equations above, equivalent to \( C \), the coefficient of stiffness in solids) is approximately given by

\[
K = \gamma \cdot p_{\text{Thus}}
\]

Thus

\[
C = \sqrt{\gamma \cdot \frac{p}{\rho}}
\]

Where: \( \rho \) is the pressure
\( \gamma \) is the adiabatic index also known as the isentropic expansion factor.

It is the ratio of specific heats of a gas at a constant-pressure to a gas at a constant-volume (\( C_p / C_v \)), and arises because a classical sound wave induces an adiabatic compression, in which the heat of the compression does not have enough time to escape the pressure pulse, and thus contributes to the pressure induced by the compression.

1.1.2 Wavelength of Sound Wave

The wavelength is the distance between two peaks, valleys, or any other corresponding points on the wave. Wavelength is inversely related to the frequency. If, frequency doubles, wavelength halves.

![Diagrammatic representation of wavelength](image)

1.1.3 Frequency of Sound Wave

The frequency is the number of cycles of oscillation per second made by the sound source and the particles in the medium. The frequency of sound, has a standard formula: \( V = f \lambda \)

Most sound waves that humans can actually hear, are frequencies from 20 – 20 000 Hz, 20 Hz would be very deep, low, rumbling sounds while 20 000 Hz would be a very high pitched, squealing noise. Audible sound frequency is called its pitch and expressed in "hertz."
1.1.4 **Amplitude of Sound Wave**

The term **amplitude** refers to the amount of change of a time varying quantity. The amount that the pressure increases (or decreases) in the medium as the sound wave travels through is called the **Pressure Amplitude**. Pressure amplitude is measured in units called **Pascals** (Pa) or **Megapascals** (MPa).

![Amplitude of sound waves](image)

1.1.5 **Loudness of Sound**

The **loudness** of a sound depends on the wave’s **amplitude**.

- The louder a sound, the greater the amplitude.
- This is also a way of measuring the amount of energy the wave has.
- The system used to measure the loudness of sounds is the **decibel system**, given the unit **dB**.
- The decibel system is based on logarithms, which means for every step up by one, the sound is actually ten times louder. For example, a 15dB sound is ten times louder than a 14dB sound.
- The decibel is actually a fraction of a bel, the original unit for measuring sound (1 db = 0.1 b). The "bel" was originally named after Alexander Graham Bell, the inventor of the telephone. Because the bel was too high a value for day-to-day situations, the decibel became a standard.

1.1.6 **Power of Sound**

Power refers to the rate at which energy is transmitted by the transducer. When considering the power from an ultrasound transducer we can think of it as the rate of energy flow over the entire beam. Power is given in **watts** (W) or in **milliwatts** (mW).

1.1.7 **Intensity of Sound**

Intensity is defined as power per unit area. One can think of it as the rate of energy flow across a defined area of the beam.

It is expressed in watts per square meter (W/m²) or in milliwatts per square cm (mW/cm²). Usually the power and the intensity are directly related. Doubling one doubles the other, and vice versa. In contrast, pressure amplitude and intensity are related through a square dependence. Specifically, the intensity, I is proportional to the pressure amplitude, A².
CHAPTER TWO
PROPAGATION OF SOUND AND FACTORS AFFECTING IT

2.0 PROPAGATION OF SOUND

Propagation of sound is the Transmission of Acoustic Energy through a medium via a sound wave. Sound is a sequence of waves of pressure, which propagates through compressible media such as air or water or solid. During their propagation, waves can be reflected, refracted, or attenuated by the medium.

In air, sound is transmitted by pressure variations from its source to the surroundings. The sound level decreases, as it gets further and further away from its source. While absorption by air is one of the factors attributing to the weakening of a sound during transmission, distance plays a more important role in noise reduction during transmission.

The reduction of a sound is called Attenuation. The effect of distance attenuation depends on the type of sound sources. Most sounds or noises we encountered in our daily life are from sources, which can be characterized as point or line sources.

For a point source, the noise level decreases by 6dB per doubling of distance from it.
If the sound source produces cylindrical spreading of sound such as stream of motor vehicles on a busy road at a distance, it may be considered as a line source.
For a line source, the noise level decreases by 3dB per doubling of distance from it.

2.1 PROPERTIES AFFECTING THE BEHAVIOUR OF SOUND PROPAGATION

All media have three properties, which affect the behavior of sound propagation:

- **A relationship between density and pressure**: this relationship, affected by temperature, determines the speed of sound within the medium.
- **The motion of the medium itself**: e.g. winds, Independent of the motion of sound through the medium, if the medium is moving, the sound is further transported.
- **The viscosity of the medium**: this determines the rate at which sound is attenuated. For many media, such as air or water, attenuation due to viscosity is negligible.

A single segment of a sound wave is characterized as pressure compressions and rarefactions.
2.2 FACTORS AFFECTING PROPAGATION OF SOUND

There are several important factors, which affect the propagation of sound: geometric spreading, atmospheric effects, and surface effects. These are discussed separately below.

2.2.1 Geometric Spreading

This refers to the spreading of sound energy as a result of the expansion of the wave fronts. Geometric spreading is independent of frequency and has a major effect in almost all sound propagation situations. There are two common kinds of geometric spreading: spherical and cylindrical spreading. Sound propagation losses due to spreading are normally expressed in terms of x dB per doubling of distance from the source.

For example, in the case of spherical spreading from a point source, which is due to a noise source radiating sound equally in all directions, the sound level is reduced by 6 dB for each doubling of distance from the source.

![Figure 5; Spherical spreading from point source](image)

A line source (producing equal sound power output per unit length of highway) will produce cylindrical spreading, resulting in a sound level reduction of 3 dB per doubling of distance.

![Figure 6; Cylindrical spreading from line source](image)

2.2.2 Atmospheric Effects

(a) Air Absorption: There are two mechanisms by which acoustic energy is absorbed by the atmosphere. These are molecular relaxation and viscosity effects. By far the most important of these is molecular relaxation. High frequencies are absorbed more than low. The amount of absorption depends on the temperature and humidity of the atmosphere. The figures show the variation of the absorption with temperature and relative humidity.

From the diagrams, it can be seen that for the middle of the speech frequency range (2 kHz), the absorption is typically .25dB/100 m for 30% relative humidity and 20°C (68°F). It should be noted, however, it could be as high as 5dB/100 m at 8 kHz when the temperature is 20°C and the humidity is 10%.
Precipitation, rain, snow, or fog, has an insignificant effect on sound levels although the presence of precipitation will obviously affect the humidity and may affect wind and temperature gradients (see next section).
Under 'normal' circumstances, atmospheric absorption can be neglected except where long distances or very high frequencies are involved.

(b) Wind and Temperature Gradients: The speed that sounds propagate in a gas depends on the temperature of the gas. Higher temperatures produce higher speeds of sound. Since the temperature of the atmosphere is not uniform, there are local variations in the sound speed. For example, under normal conditions the atmosphere is cooler at higher altitudes. This results in sound waves being 'bent' upwards. This will result in the formation of a shadow zone, which is a region in which sound does not penetrate. In reality, some sound will enter this zone due to scattering. Scattering occurs when sound waves are propagating through the atmosphere and meet a region of in homogeneity (a local variation in sound speed or air density) and some of their energy is re-directed into many other directions. In environmental noise situations, air turbulence, rough surfaces, and obstacles such as trees cause scattering. The scattering of sound by rain, snow or fog at ordinary frequencies is insignificant.
Under conditions of a temperature inversion (temperature increasing with increasing height), the sound waves will be refracted downwards, and therefore may be heard over larger distances. This frequently occurs in winter and at sundown.
When a wind is blowing, there will always be a wind gradient. This is due to the layer of air next to the ground being stationary. A wind gradient result in sound waves propagating upwind being 'bent' upwards and those propagating downwind is 'bent' downwards.

Figure 9: Wind gradients

Temperature and wind gradients can result in measured sound levels being very different to those predicted from geometrical spreading and atmospheric absorption considerations alone. These differences may be as great as 20 dB. These effects are particularly important where sound is propagating over distances greater than a few hundred meters. Temperature inversions and winds can also result in the effectiveness of a barrier being dramatically reduced.

2.2.3 Surface Effects

(a) Ground Absorption: If sound is propagating over ground, attenuation will occur due to acoustic energy losses on reflection. These losses will depend on the surface. Smooth, hard surfaces will produce little absorption whereas thick grass may result in sound levels being reduced by up to about 10 dB per 100 meters at 2000 Hz. High frequencies are generally attenuated more than low frequencies. Reflection from the ground can result in another mechanism by which sound levels are reduced. When the source and receiver are both close to the ground, the sound wave reflected from the ground may interfere destructively with the direct wave. This effect (called the ground effect) is normally noticed over distances of several meters and more, and in the frequency range of 200-600 Hz.

Figure 10: Propagation of sound over ground
(b) Attenuation Due to Barriers and Trees: Research on propagation through trees has produced conflicting results. It is clear, though, that trees are of more benefit aesthetically than acoustically. A band of trees several hundreds of feet deep is required in order to achieve significant attenuation. Significant attenuation can be achieved by the use of solid barriers. A barrier should be at least high enough to obscure the 'line of sight' between the noise source and receiver. Barriers smaller than this may have a negative effect by elimination of the destructive interference phenomenon. A barrier is most effective for high frequencies since low frequencies are diffracted around the edge of a barrier more easily. The maximum performance of a barrier is limited to about 40 dB, due to scattering by the atmosphere. A barrier is most effective when placed either very close to the source or to the receiver. It should be remembered that a barrier’s performance can be severely reduced by temperature and wind gradients.

Barriers not built for acoustical purposes are often found in sound propagation situations. The most common of these are hills and buildings. In urban situations, buildings can be effective barriers. It is possible for buildings to produce a different acoustical effect. In a street, multiple reflections from parallel building facades can result in considerable reverberation, and consequently reduced attenuation. This is often referred to as the canyon effect.

2.3 METEOROLOGICAL EFFECTS ON SOUND PROPAGATION

The weather has a fundamental influence of the sound propagation outdoors. The results from the research could be used in planning and when doing sound measurements outdoors. Errors of the order of 20dBA could be introduced if weather is not taken into account. Since 1976, investigations concerning meteorological effects on sound propagation have been carried out at the Department of Meteorology at Uppsala University. Many experimental and theoretical studies have been performed. Meteorological effects were noticeable even at a distance of twenty-five meters from the source and increased with
decreasing receiver height. The three most significant meteorological effects on sound propagation are refraction, scattering by turbulence and atmospheric absorption.

2.3.1 Refraction
Refraction of sound rays occurs if the sound velocity and/or wind speed changes along the ray path, i.e., there are gradients of wind and temperature. The refraction influences the sound level. The angle of sound incidence at the ground changes, which results in varying ground attenuation. In downwind conditions and/or temperature inversion, the sound rays are bent downwards, and in upwind conditions and/or lapse, they are bent upwards. Upwind conditions and/or lapse create areas, known as sound shadow zones, where no direct sound ray can reach. The refractive effects of temperature gradients and wind component gradients in the direction of propagation are additive. As the refractive conditions change, the path lengths of the various waves intersecting at the receiver change.

2.3.2 Turbulence
Turbulence has a twofold effect on sound propagation. First, temperature fluctuations lead to fluctuations in the velocity of sound. Secondly, turbulence velocity fluctuations produce additional random distortions of the sound wave front. Turbulence scatters sound into sound shadow zones and causes fluctuations of the phase and the amplitude of the sound waves, thus destroying the interference between different rays reaching the receiver. This gives higher sound levels than expected for frequencies where the ground effect has its maximum.

2.3.3 Atmospheric absorption
Atmospheric absorption depends on frequency, relative humidity, temperature and atmospheric pressure. A small part of a sound wave is lost to the air or other media through various physical processes. One important process is the direct conduction of the vibration into the medium as heat caused by the conversion of the coherent molecular motion of the sound wave into incoherent molecular motion in the air or other absorptive material. The viscosity of the medium also affects sound transmission. These two physical causes combine to produce the classical attenuation of a sound wave. Sound attenuation due to absorption can be calculated. Atmospheric absorption increases linearly with distance and becomes more important the longer sound propagation is under study. Very little attenuation is found for low values of relative humidity or temperature. Monthly and diurnal variations in relative humidity and temperature introduce large variations in atmospheric absorption. Usually, relative humidity reaches its maximum soon after sunrise and its minimum in the afternoon when temperature is highest. The diurnal variations are greatest during the summer.
2.4 PROPAGATION OF SOUND THROUGH DIFFERENT MEDIA

2.4.1 Propagation of Sound through Water

Sound propagation under water

How does sound velocity vary in the oceans?

Since sound speed varies with temperature, pressure and salinity there are considerable variations in sound velocity both spatially (with depth / geographically) and temporally (daily / seasonally).

Horizontal variations in sound velocity are usually small due to small gradients in T, S and p. Exceptions might occur in estuaries or around oceanic frontal systems. However, since vertical gradients in T, p and S are much larger, vertical variations in sound velocity are much larger!

The simplified schematic above shows idealized vertical profiles of temperature and sound velocity. This simplified diagram can be divided into three distinct zones.

Closest to the surface (zone 1) there is an isothermal layer created and maintained by mixing due to wind and waves. Within this layer which can be up to 200m deep the sound velocity increases slowly with depth due to the increasing pressure.

The middle layer (zone 2) is the thermocline. Here the sound velocity decreases rapidly with depth due to the decreasing temperature. The base of the permanent thermocline varies greatly with latitude but is typically found at a depth of about a 1000m.
Within the deepest region (zone 3) below the permanent thermocline the temperature change is less dramatic. Here the sound velocity shows a further increase with depth due to increasing pressure (like the surface layer).

**Sound Fixing and Ranging (SOFAR) Channels**

The form of the vertical sound profile is extremely important to the propagation of sound in the oceans. Areas that effectively trap and focus sound waves and are called 'sound channels'. These are the deep and shallow sound channels. Sound travels very efficiently in sound channels and for this reason they are often utilized for underwater communications. The deep sound channel is often called the Sound Fixing And Ranging (SOFAR) channel. The depth of the SOFAR channel varies considerably geographically. Typically it is found at around 1500m depth at mid-latitudes, has a depth of about 500m between 50 to 60 degrees north (near Britain), and reaches the surface in Polar latitudes. The average depth of the deep sound channel is approximately 1000m. The depth of the SOFAR channel is also affected by topographic features, which may promote mixing between deeper and shallower water masses thus modifying both the temperature and sound velocity profiles.

![Figure 13; the convergence of sound rays around velocity minima (sound channels)](image)

Close examination of the figure above shows that the thermal structure within the water column not only leads to a focusing acoustic energy but also can give rise to other areas of acoustic darkness or 'shadow zones'. This also has important implications in underwater acoustics. For example, it would be impossible to detect an enemy submarine with sonar if it were positioned in the shadow zone! Before the concepts of shadow zones were fully understood (before World War II) there was no explanation of the mysteriously weak echoes that were obtained in the afternoon when previously detection had been good in the morning. At first sonar, operators were blamed for their poor performance in the afternoon. We now know that the weak echoes in the afternoon were due to the development of the
diurnal thermo cline resulting from a warming of the water column by the sun throughout the day. This phenomenon is now known as 'the afternoon effect'.

2.4.2 Propagation of Sound Outdoors

Sound energy in the propagation direction of the sound is inversely proportional to the increasing surface area the sound propagates. The sound pressure level in a spherical distance - \( r \) - from a single sound source can be expressed as:

\[
L_p = L_w - 10 \log (4 \pi r^2) \quad (1), \text{ can also be expressed as } \{L_p = L_w - 20 \log(r) + K'\} \quad (1b)
\]

Where, \( L_p \) = sound pressure level (dB)

\( L_w \) = sound power level source in decibel (dB)

\( r \) = distance from source (m)

**Single Sound Source - Hemi Spherical Propagation**

When the sound source propagates hemi spherically with the source near ground, the constant can be set to

\( K' = -8 \)

**Note:** When the distance - \( r \) - from a power source doubles, the sound pressure level decreases with 6 dB. This relationship is also known as the inverse square law.

Other factors affecting the radiation of the sound are the direction of the source, barriers between the source and the receiver, and atmospheric conditions. Equation (1) can be modified to:

\[
L_p = L_w - 20 \log r + K' + D - A_s - A_b \quad (2)
\]

**Linear Sound Source**

With a linear sound source, like a road or highway with heavy traffic, the sound pressure can be expressed as:

\[
L_p = L_w - 10 \log (4 \pi r) \quad (3)
\]

**Note:** When the distance - \( r \) - from a linear power source doubles, the sound pressure level decreases with 3 dB.

2.4.3 Transmission of Sound through and around Barriers

If a barrier is interposed between a sound source and a receiver, part of the sound

- reflected back from the barrier
- transmitted through the barrier
- diffracted around the barrier
Reflection

Reflection of sound waves off of surfaces can lead to one of two phenomena - an echo or a reverberation. A reverberation often occurs in a small room with height, width, and length dimensions of approximately 17 meters or less.

Reflection of sound waves also leads to echoes. Echoes are different from reverberations. Echoes occur when a reflected sound wave reaches the ear more than 0.1 seconds after the original sound wave was heard. If the elapsed time between the arrivals of the two sound waves is more than 0.1 seconds, then the sensation of the first sound will have died out. In this case, the arrival of the second sound wave will be perceived as a second sound rather than the prolonging of the first sound. There will be an echo instead of a reverberation.

Reflection of sound waves off of curved surfaces is also effected by the shape of the surface. Flat or plane surfaces reflect sound waves in such a way that the angle at which the wave approaches the surface equals the angle at which the wave leaves the surface. Reflection of sound waves off of curved surfaces leads to a more interesting phenomenon. Curved surfaces with a parabolic shape have the habit of focusing sound waves to a point. Sound waves reflecting off of parabolic surfaces concentrate all their energy to a single point in space; at that point, the sound is amplified.

Diffraction

Diffraction involves a change in direction of waves as they pass through an opening or around a barrier in their path. The amount of diffraction (the sharpness of the bending) increases with increasing wavelength and decreases with decreasing wavelength. In fact, when the wavelength of the waves is smaller than the obstacle or opening, no noticeable diffraction occurs.

2.4.4 Propagation of Sound Indoors

Sound and noise in a room will reach the receiver as direct and reverberant sound.
For a continuing sound source in a room, the sound level is the sum of direct and reverberant sound. The sound pressure for a receiver can be expressed as:

$$L_p = L_w + 10 \log \left( \frac{D}{4 \pi r^2} + 4 / R \right) \quad (1)$$

Where,

- $L_p = \text{received sound pressure level (dB)}$
- $L_w = \text{sound power level from source (dB)}$
- $D = \text{directivity coefficient}$
- $R = \text{room constant (m}^2 \text{ Sabin)}$
- $\pi = 3.14$
- $r = \text{distance from source (m)}$

### 2.5 CONCLUSION

It can be concluded from the above mentioned facts about the propagation of sound waves that though we cannot physically grasp them, they possess properties that make them a physical entity. The study of the physical properties and the movement of sound waves in different media is one that is vital in the determination of the acoustic properties of varying building materials, finishes and components which will in turn affect the design of buildings to be acoustically sound and efficient.

### 2.6 REFERENCES


