A

TERM PAPER

ON

THE BEHAVIOUR OF SOUND IN AN ENCLOSED SPACE

(GROUP 12)

SUBMITTED TO:

DEPARTMENT OF ARCHITECTURE

FEDERAL UNIVERSITY OF TECHNOLOGY

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1.0 **INTRODUCTION**

Basically, acoustics being the science of sound is apparently abstract to all. Sound unlike mechanics is not something we can see but can only be perceived through the sensation of hearing. Sound can be described as a disturbance or turbulence which passes through a physical medium in the form of longitudinal waves from a source to a receiver causing a sensation of hearing. This medium could be solid, fluid or gas. The speed of sound through these different media differs due to their molecular composition.

The nature of sound has been a subject of study since ancient times. As early as 500 B.C. it was well known that sound is produced by vibrating objects. For example the Greek Philosopher and mathematician conducted experiments around 500 B.C. conducted experiments on sound produced by vibrating strings. Around 350 B.C. Aristotle stated that the sound is carried to our ears by movement of air. But the realization that such movement was in the form of waves was not there.

Although people have gathered in large auditoriums and places of worship since the advent of civilization, architectural acoustics did not exist on a scientific basis until a young professor of physics at Harvard University accepted an assignment from Harvard’s Board of Overseers in 1895 to correct the abominable acoustics of the newly constructed Fogg Lecture Hall. Through careful (but by present-day standards, rather crude) measurements with the use of a Gemshorn organ pipe of 512 Hz, a stopwatch, and the aid of a few able-bodied assistants who lugged absorbent materials in and out of the lecture hall, Wallace Sabine established that the reverberation characteristics of a room determined the acoustical nature of that room and that a relationship exists between quality of the acoustics, the size of the chamber and the amount of absorption surfaces present. He defined a reverberation time $T$ as the number of seconds required for the intensity of the sound to drop from a level of audibility 60 dB above the threshold of hearing to the threshold of inaudibility. To this day reverberation time still constitutes the most important parameter for gauging the acoustical quality of a room.

Deployment of absorbing materials throughout the room. This accomplishment firmly established Sabine’s reputation, and he became the acoustical consultant for Boston Symphony Hall, the first auditorium to be designed on the basis of quantitative acoustics.

Bearing in mind the properties of sound, this term paper tends to study the behaviour of sound within an enclosure, means of improving room acoustics through installation of appropriate materials.

The sound waves will be spherical and the intensity wills approximately the inverse square law. Neither reflection nor diffraction occurs to sound with the room boundaries and with objects within the room; the free field will be of very limited extent.
If one is close to a sound source in a large room having considerably absorbent surfaces, the sound energy will be detected predominantly from the sound source and not from the multiple reflections from surrounding surfaces are lined with almost totally absorbent materials. Diffuse Sound reflected from walls generate a reverberant field that is time dependent. When the source suddenly ceases, a sound field persists for a finite interval as the result of multiple reflection and the low velocity of sound propagation. This residual acoustic energy constitutes the reverberant field. The sound that reaches the listener in a fairly typical auditorium can be classified into two broad categories:

- The Direct (free field) sound.
- Indirect (reverberant) sound.

![Diagram of direct and indirect sound](image)

*Fig.1. Direct and indirect sound*

1.1 **DIRECT AND INDIRECT SOUND**

The amount of acoustic energy reaching the listener’s ear by any single reflected path will be less than that of the direct sound because the reflected sound is longer than the direct source-listener distance, which result in greater divergence; and all reflected sound undergo an energy decrease due to the absorption of even the most ideal reflectors. But indirect sound that a listener hears comes from a great number of reflection paths. Consequently, the contribution of reflected sound to the total intensity at the listener’s ear can exceed the contribution of direct sound particularly if the room surfaces are highly reflective.
The phases and the amplitudes of the reflected waves are randomly distributed to the degree that cancellation from destructive interference is fairly negligible. If a sound source is operated continuously the acoustic intensity builds up in time until a maximum is reached. If the room is totally absorbent so that there are no reflections, the room operates as an anechoic chamber, which simulates a free field condition. With partial reflection, however, the source continues to add acoustic energy to the room, that is partially absorbed by the enclosing surfaces (i.e., the wall, ceiling, floor and furnishings) and deflected back into the room. For a source operating in a reverberation chamber the gain in intensity can be considerable as much as ten times the initial level. The gain in intensity is approximately proportional to reverberation time; thus it can be desirable to have a long reverberation time to render a weak sound more audible.

In this term paper we shall succinctly examine the behaviour of sound in an enclosed space as well as the factors that affect the behaviour of sound in an enclosed space.

1.2 DEFINITION OF TERMS

- **Sound** is a disturbance of the atmosphere that human beings can hear. Such disturbances are produced by practically everything that moves, especially if it moves quickly or in a rapid and repetitive manner. A sound wave is characterized by its velocity, frequency, wavelength and amplitude. The frequency is the number of waves per unit time while the velocity is the product of the wavelength and the frequency. See figure 3. The amplitude indicates the intensity of the sound. The power of the source is measured in watts (W) while the intensity is measured in watts per square metre (W/m²).

- **Wavelength of sound** – This the distance between two pressures peaks or valleys measured in metres (m) and represented with the Greek alphabet ‘λ’ (lambda).
- **Period** – This is the time taken for one complete oscillation. This is measured in seconds (s) and represented with the letter ‘T’.
- **Frequency** – This is the number of oscillations per second. This is represented with ‘f’ and measured in Hertz (Hz).
- **Velocity of sound** – This is the rate at which a sound wave travels from a source through a medium to the receiver. The unit is m/s.
- **Amplitude** – This is the distance between a crest (the highest point) and a valley (the lowest point).
- **Pitch** – it is the highness or lowness of a tone determined by the rapidity of the oscillations producing it.

The above mentioned properties of sound determine the behaviour of sound generally either in an open or enclosed space. These factors are used to describe sound especially in music, in its study, arrangement of sounds, the music scale, tunes and others.
1.3 HOW SOUND MOVES

The notion of sound is rather remarkable. Something happens there and we know it here, even if we are looking the other way, not paying attention, or even asleep. The fact that some sounds can produce physical and emotional effects is really amazing.

It is a known fact that, air is made up of molecules. Most of the characteristics we expect of air are a result of the fact that these particular molecules are very light and are in extremely rapid but disorganized motion. This motion spreads the molecules out evenly, so that any part of an enclosed space has just as many molecules as any other. If a little extra volume were to be suddenly added to the enclosed space (say by moving a piston into a box), the molecules nearest the new volume would move into the recently created void, and all the others would move a little farther apart to keep the distribution even.

Because the motion of the molecules is so disorganized, this filling of the void takes more time than you might think, and the redistribution of the rest of the air molecules in the room takes even longer. If the room were ten feet across, the whole process might take 1/100 of a second or so.
If the piston were to move out suddenly, the volume of the room would be reduced and the reverse process would take place, again taking a hundredth of a second until everything was settled down. No matter how far or how quickly the piston is moved, it always takes the same time for the molecules to even out.

In other words, the disturbance caused by the piston moves at a constant rate through the air. If you could make the disturbance visible somehow, you would see it spreading spherically from the piston, like an expanding balloon. Because the process is so similar to what happens when you drop an apple into a bucket, we call the disturbance line the wave front.

If the piston were to move in and out repetitively at a rate between 20 and 20,000 times a second, a series of evenly spaced wave fronts would be produced, and we would hear a steady tone. (One wave front is heard as a click.) The distance between wave fronts is called wavelength.
2.0 BEHAVIOUR OF SOUND IN AN ENCLOSED SPACE

2.1 REFLECTION, REFRACTION, DIFFRACTION AND ABSORPTION

Sound wave doesn't just stop when it reaches the end of the medium. Rather, the wave will undergo certain behaviors when it encounters the end of the medium. Specifically, there will be some reflection off the boundary and some transmission into the new medium. What if the wave is traveling in a three-dimensional medium such as a sound wave traveling through air? What types of behaviors can be expected of such three-dimensional waves?

2.1.1 REFLECTION

Reflection of sound waves encompasses two phenomena namely; echo and reverberation. Reverberation often occurs in a small room with height, width, and length dimensions of approximately 17 meters or less. Why the magical 17 meters? The affect of a particular sound wave upon the brain endures for more than a tiny fraction of a second; the human brain keeps a sound in memory for up to 0.1 seconds. If a reflected sound wave reaches the ear within 0.1 seconds of the initial sound, then it seems to the person that the sound is prolonged. The reception of multiple reflections off of walls and ceilings within 0.1 seconds of each other causes reverberations - the prolonging of a sound. Since sound waves travel at about 340 m/s at room temperature, it will take approximately 0.1 s for a sound to travel the length of a 17 meter room and back, thus causing a reverberation.

This is why reverberations is common in rooms with dimensions of approximately 17 meters or less. Perhaps you have observed reverberations when talking in an empty room, when honking the horn while driving through a highway tunnel or underpass, or when singing in the shower. In auditoriums and concert halls, reverberations occasionally occur and lead to the displeasing garbling of a sound.

2.1.1.0 AUDITORIUM AND CONCERT HALL

Reflection of sound waves in auditoriums and concert halls do not always lead to displeasing results, especially if the reflections are designed right. Smooth walls have a tendency to direct
sound waves in a specific direction. Subsequently the use of smooth walls in an auditorium will cause spectators to receive a large amount of sound from one location along the wall; there would be only one possible path by which sound waves could travel from the speakers to the listener.

The aim of the design of a listening type of facility is to avoid the following acoustic defects (Siebein, 1994).

- **Echoes**, particularly those from the rear walls of the facility. Echoes can be lessened or eliminated by placing absorbent panels or materials on the reflecting walls or introducing surface irregularities to promote diffusion of the sound.

- **Excessive loudness** can occur from prolonged reverberation. Again, the proper deployment of absorbent materials should alleviate this problem.

- **Flutter echo** results from the continued reflection of sound waves between two opposite parallel surfaces. This effect can be especially pronounced in small rooms; and this can be contravened by splaying the walls slightly (so as to avoid parallel surfaces) or using absorbent material on one wall.

- **Creep** is the travel of sound around the perimeter of domes and other curved surfaces. This phenomenon is also responsible for whispering gallery effects in older structures with large domed roofs.

- **Sound focusing** arises when reflections from concave surfaces tend to concentrate the sound energy at a focal point.

- **Excessive or selective absorption** occurs when a material that has a narrow range of acoustical absorption is used in the facility. The frequency that is absorbed is lost, resulting in an appreciable change in the quality of the sound.

- **Dead spots** occur because of sound focusing or poorly chosen reflecting panels.

Rough walls tend to diffuse sound, reflecting it in a variety of directions. This allows a spectator to perceive sounds from every part of the room, making it seem lively and full. For this reason, auditorium and concert hall designers prefer construction materials which are rough rather than smooth. 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. Perhaps you have seen a museum exhibit which utilizes a parabolic-shaped disk to collect a large amount of sound and focus it at a focal point. If you place your ear at the focal point, you can hear even the faintest whisper of a friend standing across the room. Parabolic-shaped satellite disks use this same principle of reflection to gather large amounts of electromagnetic waves and focus it at a point. Reflection of sound waves
also leads to echoes. Echoes are different than reverberations. Echoes occur when a reflected sound wave reaches the ear more than 0.1 seconds after the original sound wave was heard.

2.1.2 **REFRACTION**

Refraction of waves involves a change in the direction of waves as they pass from one medium to another. Refraction, or bending of the path of the waves, is accompanied by a change in speed and wavelength of the waves. So if the medium (and its properties) are changed, the speed of the waves is changed. Thus, waves passing from one medium to another will undergo refraction. Refraction of sound waves is most evident in situations in which the sound wave passes through a medium with gradually varying properties. For example, sound waves are known to refract when traveling over water. Even though the sound wave is not exactly changing media, it is traveling through a medium with varying properties; thus, the wave will encounter refraction and change its direction. Since water has a moderating affect upon the temperature of air, the air directly above the water tends to be cooler than the air far above the water. Sound waves travel slower in cooler air than they do in warmer air. For this reason, the portion of the wavefront directly above the water is slowed down, while the portion of the wavefronts far above the water speeds ahead. Subsequently, the direction of the wave changes, refracting downwards towards the water.

2.1.3 **DIFFRACTION AND INTERFERENCE**

Diffraction involves a change in direction of waves as they pass through an opening or around a barrier in their path. When the wave front hits a wall with a hole in it a small portion of the wave energy leaks through the hole and begins propagating as if the hole were the source, that is, spherically around the hole. The amount of energy available depends on the size of the hole. This process is known as **diffraction**.

![Fig.4 showing diffraction and interference of sound wave](image-url)
An interesting effect is created when there are two holes in the wall. Each hole produces a wave front, and the two separate wave fronts coincide at some point. If you happened to measure the strength of the wave at that point, the energies of both fronts would be combined, and the measurement would be quite different from one obtained only a few inches away. This effect is called **interference**.

### 2.1.4 SOUND ABSORPTION

![Sound absorption diagram](Fig.5)

**Fig.5 sound absorption**

Sound absorption is defined, as the incident sound that strikes a material that is not reflected back. An open window is an excellent absorber since the sounds passing through the open window are not reflected back but makes a poor sound barrier. Painted concrete block is a good sound barrier but will reflect about 97% if the incident sound striking it. All building materials have some acoustical properties in that they will all absorb, reflect or transmit sound striking them. Acoustical materials are those materials designed and used for the purpose of absorbing sound that might otherwise be reflected.

When a sound wave strikes an acoustical material the sound wave causes the fibers or particle makeup of the absorbing material to vibrate. This vibration causes tiny amounts of heat due to the friction and thus sound absorption is accomplished by way of energy to heat conversion. The more fibrous a material is the better the absorption; conversely denser materials are less absorptive. The sound absorbing characteristics of acoustical materials vary significantly with frequency. In general low frequency sounds are very difficult to absorb because of their long wavelength. On the other hand, we are less susceptible to low frequency sounds, which can be to our benefit in many cases.
2.1.5 **TRANSMISSION**

In this phenomenon, sound wave is carried by molecules of the obstacle through vibration and re-emitted at the other side irrespective of the medium. It can be *structure borne, air borne or impact sound.*

![Diagram of sound transmission](image)

*Fig. 6 sound Transmission*

2.1.6 **REVERBERATION AND ECHO**

- **Reverberation:** This is the persistence of sound in an enclosed space as a result of continuous reflection or scattering of sound after the source has stopped. It is one the most prominent behaviour of sound in an enclosure. It occurs when sound waves hits a surface and are reflected toward another surface which also reflects it. Some of the sound is absorbed with this continuous reflection which gradually reduces the energy of the sound to zero. The phenomenon can affect the audibility of sound in an enclosure, especially if the reverberation time, which is the time taken for the sound pressure level to diminish to 60 dB below its initial value is considerably long.

- **Echo:** this occurs when the reverberation time is long enough to cause a distinct repetition of the direct sound. This condition is an advanced form of reverberation where the sound is heard clearly and repeatedly after some time until it fades.
3.0 FACTORS AFFECTING SOUND BEHAVIOUR OF SOUND IN AN ENCLOSED SPACE

- The farther away sound is from the source, the less its intensity i.e. sound intensity dies out over distance.
- The angle of incidence is equal to the angle of reflection.
- Harmonics of a single sound travel differently.
- Sound travels at constant speed (speed of sound), and so is delayed depending on distance to perceiver.
- The perceiver in a room will also hear the echo resulting from the walls, ceiling, and floors, low frequency.
- Barrier that obstruct or prevent sound transmission cause sound shadow to occur.
- Surface absorption of direct and reflected sound.
- Part of the sound wave curves around the edge of a barrier this is known as edge diffraction.

4.0 CONCLUSION

Sound as a mechanical wave is interestingly characterized by many uniqueness especially within an enclosed space. The acoustic analysis is an important data for the design of any space especially in the design of large enclosed spaces designed for speech, music or quiet. This stresses the relevance of acoustic to the field of architecture.

However, having carefully studied the behaviour of sound within an enclosed space, an inference can be drawn that the importance of the adequate knowledge of this subject cannot be over-emphasized. It is imperative that the understanding of the behaviour of sound and related issues within a confinement is a prerequisite in achieving acoustically functional spaces by architects and this must be taken into strict consideration right from the inception stage of a design to the construction completion stage.
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