Global Scientific JOURNALS

GSJ: Volume 9, Issue 2, February 2021, Online: ISSN 2320-9186
www.globalscientificjournal.com

ARCHITECTURAL ACOUSTICS: INVESTIGATING THE EFFECTS OF BUILDING FORMS ON ACOUSTICS.

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KeyWords
Architectural acoustics, Building Acoustics, Building forms, Soundwaves, Shoebox shape, Auditorium, Whispering Gallery.

ABSTRACT

Most large spaces share a common challenge, which is poor sound management and control. Large spaces by necessity are conditioned by the need of all within it, to have a clear view of the stage and to hear the facilitator or actors on stage audibly. In life, the sound is as important as light. Light gives humans the visual connection to reality, while sound gives meaning to existence and differentiation. Architects and designers are constantly coming up with design suggestions to solve the challenge of acoustics in large spaces and this is one of the key reasons we now have auditoriums shaped in such a way that the audience will be close to the sound source and free from noise as much as possible. Hence, the authors investigate how the form of a building affects the quality of sound produced and transmitted within it. The work begins with a brief analogy of the application of sound in ancient times; the definition of sound and its concept as it relates to acoustics. Furthermore, various forms are taken into consideration, and their influence on sound is taken cognizance of. At the end of the research, the author seeks to establish the fact that, the behaviour of sound on a surface is determined by the shape of such surface and the material it is made of. It is well known that building materials and some other factors can also affect acoustics, but this research work is intended to investigate the effects of building forms on acoustics and suggest possible ways to achieve a sonically viable room space. To achieve this research work, the author has painstakingly explored several works of literature that deal on the issues of acoustics, also has visited some halls, both physically and via the internet, to take a look at how acoustics has been handled.

1.0 Introduction

As the global population continues to grow, the need for larger spaces like halls, theatres and conference centres grows alongside it. We now have more people attending schools, churches, events, etc. Halls meant for 50 persons are now used to house more than what it was designed for. Hence, the challenge to make sure that provision for good acoustics is not overlooked, confronts us on our way to providing larger spaces. And the larger space, the more the acoustic challenges to be encountered. Around us are quite a several structures that have been put up without any acoustic considerations for the interior spaces. This is quite evident in the rate at which spaces like warehouses are being converted to event halls, and even churches. This trend, for sure, has heaped up a workload for architects and acousticians; it will take their joint effort to remedy the situation. On our journey to investigating and tackling the problems of acoustics, it is expedient to begin by addressing the root matter – 'sound'.

During the ancient wars, people often gathered intelligence about enemies with the help of sounds transmitted through the ground. The early fishermen carried out their fishing surveys with the help of sounds produced beneath the water. They do this by leaning down in the cabin with their ears close to the bottom to hear the sound produced by shoals. One of the oldest means of communication was through sounds and gestures even before the inventions of modern languages. That is why sound, just like graphics, is a language in itself.

*'Sound is a language in itself, a universal lingua franca'. (*Bright Izuu Joseph et al, 2021)

Large spaces have the problem of long reverberation times. This can be so offensive in an environment where members of the audience are required to pay rapt attention to and hear clearly to what is being performed or presented. When the acoustics of a space is poor, it can make listeners suffer from a vestibular disorder. Voices get drowned in echoes and the sound of music becomes nothing but irritating noise to the listener. To solve this problem of reverberation, sound reflection needs to be brought to its barest minimum. The kind of form adopted during the design process can either be a solution to the problem or the root cause. Simply put, the form of a building (internally) has a direct effect on acoustics. (Enokela & Dr. M.L, 2015)

Sabine, 1992 followed the earlier European example: with the use of a shoe boxed-shape and heavy plaster swung into construction, coupled with a modest ceiling height to maintain a reverberation time of 1.8 seconds. Furthermore, the introduction of the narrow side and rear balconies aided the avoidance of shallow zones and shallow stage enclosure. The result of this is that: the angled walls and ceiling redirected the orchestra sound out to the audience; the deeply coffered ceiling and wall niches containing classical statuary provide excellent diffusions. This paper will investigate various existing concert halls and other geometrical forms of architecture and the effect on the acoustics. This research work begins by explaining what sound is and how it moves from the source, reflected, absorbed, diffused and even transmitted. It also reveals what causes echo and noise and how this can be controlled or eliminated using certain Architectural Geometry.

2.0 Aim and Objectives

Some of the aim and objectives of this study include:

1. To investigate the effect of building forms on acoustics.
2. Identify ways to improve and provide good sound quality in large and medium-size spaces, like a conference centre.
3. To determine reverberation time and providing an optimum reverberation time in an acoustical design of auditoriums to enhance intelligibility.
4. To encourage the provision of conducive environments that meet the audio-visual needs of all members of an audience.

3.0 Research Questions

Given the objectives of this study, the following pertinent questions are asked. They are:

1. How do you design an auditorium to eliminate unwanted reflections and echoes to improve the quality of the sound heard by the audience?
2. What kind of form is the most appropriate when considering acoustics in large indoor spaces?
3. How is reverberation time determined and how do we optimize the reverberation time to ensure good acoustics?
4. In addition to the building form, what other measures are required to achieve the good sound in an auditorium?

4.0 Sound

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 hearings. Its medium could be solid, liquid or gas. The speed of sound through this different medium differs due to their molecular compositions and temperature. That is, sound travels through air at a speed of about 340 meters per second under ordinary conditions. Sound is caused by vibration. The sound produced by human beings when speaking or singing is also caused by vibration. The sound generator of a human being is the 'Larynx' and sound can only be produced by the vibration of this organ with the support of the thorax, abdomen, nasal cavity, mouth cavity, tongue and even the skull involved in the sound production. During spreading of sound waves, each air particle only vibrates near its original place and does not migrate either. Air particles vibrate to and fro along the direction of spreading of sound waves. Waves with such characteristics are called longitudinal waves. In essence, sound waves are just longitudinal waves. Sound is generally characterized by continuous and regular vibrations, as opposed to noise which is characterized by more irregular fluctuations. In subjective terms, noise might be considered to be an unpleasant sound that causes disturbance which could harm human health and quality of life. Experimental determinations have shown that human beings can hear the sound of 20-20,000 Hz. The sound with a frequency of less than 20 Hz. Is called sub-sound, while that of more than 20,000 Hz. Super-sound. Sub-sound and super-sound are the propagation of vibrations of a sound source in media, i.e. waves in media. Therefore, they are called by a joint name 'sound waves'.

Sound is a variation in pressure detectable by the ear, whereas noise is undesired sound or any sound which causes disturbance or annoyance to the recipient. The unit used to describe sound wave intensity is in decibels (dB). Sound strength lower than 20 decibels is regarded as faint, normally speaking voices are around 65 dB. A rock concert can be around 120 dB. Over 85 dB for extended periods can cause permanent hearing loss and the higher the sound pressure, the less time it takes to cause damage. For example, a sound of 85 dB may take 8 hours to cause damage, whereas a sound of 100 dB may start to cause damage after only 30 minutes. A sound of around 150 dB can cause instantaneous hearing damage. (Designing buildings Wiki, 2020).

All materials transmit, absorbs and reflects sounds due to the presence of molecules inside in varying coefficient and frequencies. To quantify how much sound is reflected into the room, we use a metric called the absorption co-efficient ‘C’ and denote it with the Greek letter ‘α’. The absorption coefficient is one of those measurements that ranges between 0-1. ‘1’ means no sound energy is reflected, everything is absorbed or transmitted and ‘0’ means 100% of the sound is reflected; but here is the thing: reaching a point where the absorption comes to zero is nearly impossible e.g. The absorption co-efficient of the smooth concrete surface is about α 0.02 which means only 2% of the sound is absorbed and over 90% is reflected! That’s a lot. When you apply fabric glass fibre and is mounted on a frame with air space behind it, the absorption coefficient is about 0.95, so only 5% of the sound energy is reflected. An effective sound absorber will have sound absorption co-efficient > 0.75 while and effective reflector will generally have a sound absorption coefficient of < 0.20 so at least 80% of the sound is reflected.

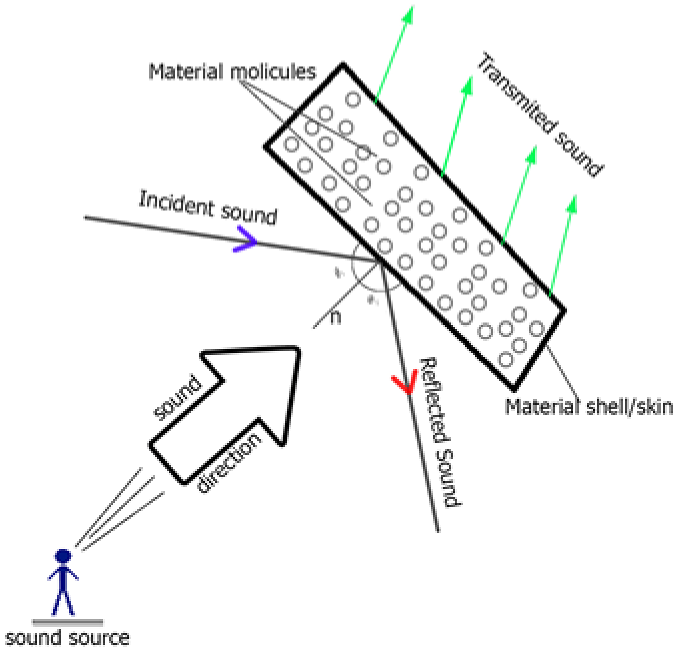

Figure 4.1 Movement of a sound wave from the source

4.1 Sound Reflection

When sound travels in a giving medium from a source, it strikes the surface of another medium and bounces back in other directions. This phenomenon is called ‘the reflection of sound’. The waves are called the ‘incident’ and ‘reflected’ sound waves. Different surface reacts differently to sound waves i.e. hard surfaces will reflect almost all of the incident sound energy; a convex surface will disperse sound while the concave surface will concentrate the reflected sound.

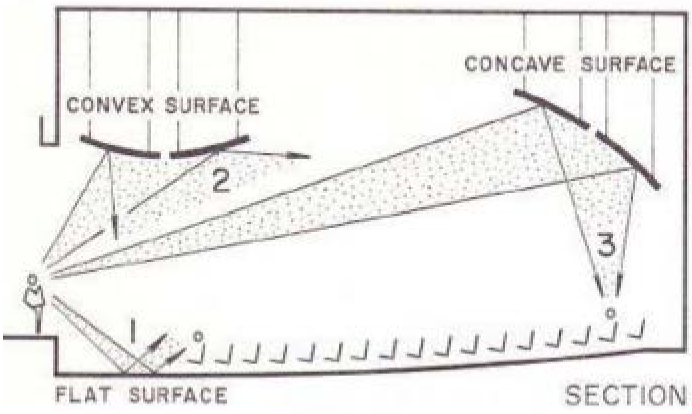

Figure 4.2 Sound reflection diagram (Joanna, et al., 2015)

In large spaces, uniform distribution of sound is usually the goal of sound technicians. Therefore, concave surfaces in these spaces usually make it difficult for the achievement of good sound, it ends up being focused to one point as shown in figure 4.2. For this reason, proper use of reflective materials become key to solving the problem. A convex surface or form will rather reflect the sound at different angles evenly distributed, almost at the same initial energy from the source. Large flat reflective surfaces are to be avoided because of the prominent reflection which will be produced. Parallel flat walls can produce a pattern of reflections known as a "flutter echo" as the sound waves travel back and forth between the surfaces.

Such flutter echoes are often encountered in high school gymnasiums where there are parallel sidewalls and also a reflective floor and ceiling.

4.2 Reverberation Time

Reverberation is the continuing presence of audible sound after the producing of sound has stopped. It is affected by the reflective properties of the surfaces in the hall or acoustic room. A reflective surface will cause the sound to die away in a long time, while an absorbance surface will cause the sound to die away quickly. Reverberation time is the length of time for the sound pressure level in a room to decrease by 60dB from its original level after the sound is stopped. It is dependent upon a few factors, the volume of the enclosure (distance), total surface area, and the absorption coefficients of the surface.

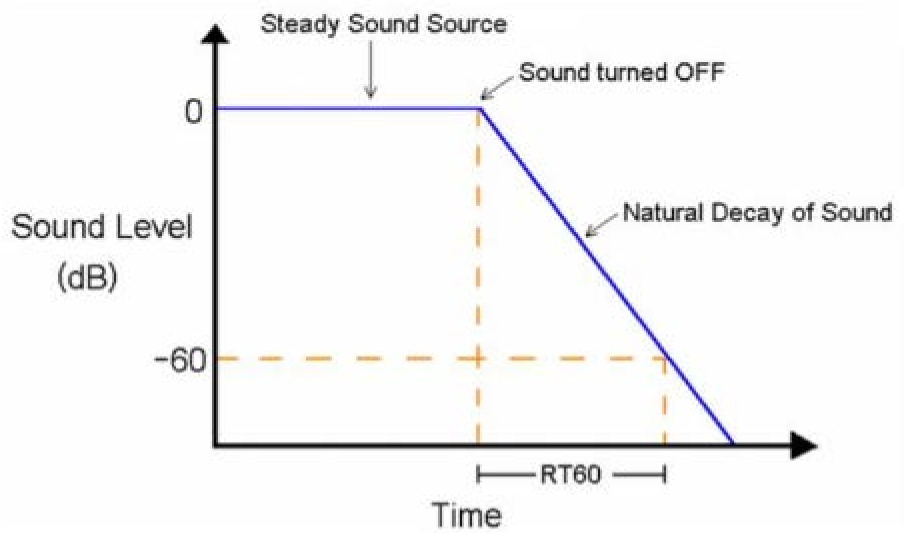

Figure 4.3 Reverberation time diagram. (Troldtekt, 2020)

4.3 Flutter Echo

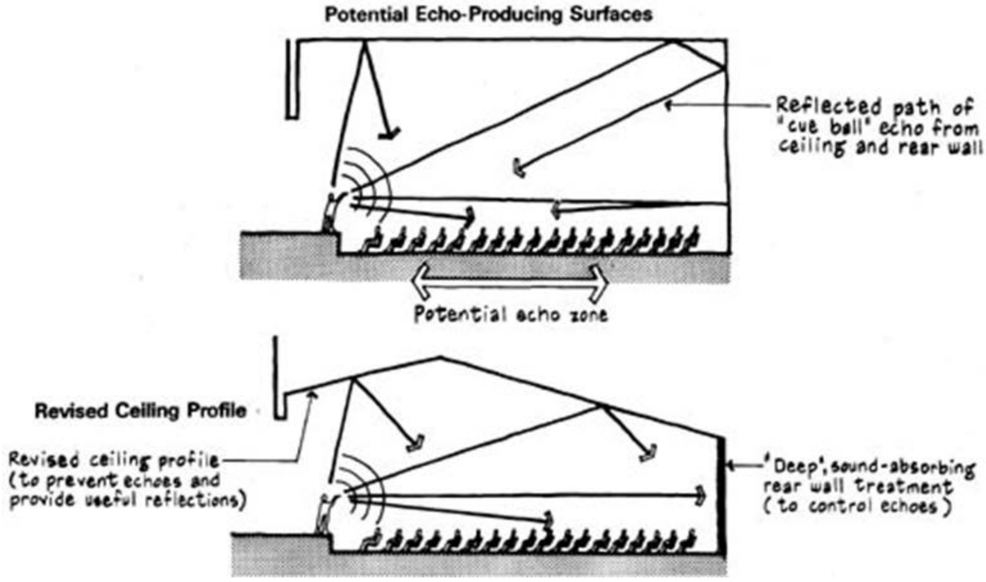

Figure 4.4 Potential Echo-Producing Surfaces; Revised Ceiling Profile (To prevent echoes and distribute sound evenly) source: (industrial-electronics, 2010)

Flutter echo sometimes called 'a repetitive echo' occurs when sound rapidly reflects back and forth between two acoustically reflective, parallel surfaces. I.e. percussive sounds, like a hand clap, bounce rapidly between one or more sets of parallel surfaces, producing a "fluttery" sound. Potential echo-producing surfaces can be treated by changing the geometry of one of the surfaces so that they are at least 10 degrees out of parallel. This will also improve the dispersion of sound throughout the room. Figure 4.4 shows how the front portion of the ceiling is lowered to reduce the delayed reflections from overhead and reoriented to provide useful reflections toward the rear of the auditorium.

Flutter echo is most obvious and problematic when two or more parallel walls are finished using hard, reflective materials. Absorption and/or diffusion can be used to mitigate problematic echoes.

4.4 Acoustic Design

Acoustics is the branch of physics concerned with the study of sound. The science of production, control, transmission, reception and effects of sound as travels through a medium (solid, liquid and gas).

Acoustic design is the intelligent combination of Architectural and engineering techniques/principles to control the behaviour of sound in an enclosed space (in this case building). The purpose is to enhance the distribution of sound within the enclosed space. The acoustic design aims at eliminating noise that would negatively affect the intelligibility of sound. Acoustics is the science of sound. Sound is central to our lives, and so it cuts across many different scientific and engineering disciplines.

Room and building acoustics (together called architectural acoustics) relate to the control of sound and vibration as it travels through buildings, as well as the sound characteristics within individual rooms. (Miller Goodall, 2020)

4.5 Room Acoustics

Room acoustics is the study of the parameters of energy impulse response which quantifies various sound attributes in the room such as loudness, tone, blurry, dry etc. and the use of Architectural and engineering techniques/principles to control the behaviour of sound in room space, auditorium, concert halls, opera halls etc.

“Room Acoustics” is the field of acoustics that describes how sound propagates in a closed or semi-closed space. Each space has its own sound ‘fingerprint’ which affects the quality of a sound, whether this is speech, music or any kind of noise. (Odeon, 2020). The main consideration or acoustic parameter for room acoustics is reverberation time (RT), which is a measurement of the time it takes for sound to decay within a space. Shorter RTs result in quieter noise levels and better speech intelligibility and are generally the goal for most spaces.

However, exceptionally short RTs are not necessarily preferable and can result in a poor projection of speech across a room (e.g. a large classroom or school hall), or a lack of liveliness and atmosphere in bars and restaurants. Shorter RTs are achieved by the inclusion of areas of acoustically absorbent surface finishes throughout the space.

Longer RTs are generally preferable within music venues such as concert halls, theatres and nightclubs where, up to a certain point, they can contribute to a variety of desirable subjective impressions relating to loudness, energy, warmth, envelopment, intimacy and excitement. (Miller Goodall, 2020)

Room acoustic can be effectively achieved when the designers pay attention to the treatment of the walls, floors, and ceilings. The form of the interior space is also an essential functional part as well as the elements, building materials and objects of Art & décor.

4.6 Building Acoustics

Building acoustics is the science of controlling noise transmission from one place to another and the control of the characteristics of sound within the spaces themselves. The main acoustic parameter for building acoustics is sound insulation, where the transfer of sound (usually considered noise) is minimised as much as possible and following any applicable acoustic regulations and design criteria. Effectively controlling all potential noise sources in a building, involves working closely with architects and building engineers to develop specifications for building materials (façade build-ups, glazing and curtain walling specifications, wall and floor constructions). Equally important is the consideration of construction detailing at junctions between building elements. (Miller Goodall, 2020). Building acoustics can be influenced by:

- The geometry and volume of space.
- The sound absorption, transmission and reflection characteristics of surfaces enclosing the space and within the space.
- The sound absorption, transmission and reflection characteristics of materials separating spaces.
- The generation of sound inside or outside within the environment.
- Airborne sound transmission.
- Impact noise.

Room and building acoustics (together called architectural acoustics) relate to the control of sound and vibration as it travels through buildings, as well as the sound characteristics within individual rooms (designing buildings Wiki, 2020)

4.7 Whispering Gallery as an Acoustic concept

This is a concept achieved when a circular, hemispherical elliptical enclosure, often beneath a dome or vault is introduced. This is mostly constructed in such a way that allows whispered communications to be heard from any part of the internal circumference of the gallery or space. As magical as it seems, it is made possible by the movement of what is described as ‘whispering-gallery waves’. These waves travel around the internal circumference of the gallery, clinging to the walls, making it possible for any whispered communication made on the gallery to be heard from any other part of the gallery. Some examples where this principle has been applied are the Whispering Gallery of the St Paul’s Cathedral, London and the Echo Wall of the Temple of Heaven, Beijing.

Whispering Gallery: Whispering-gallery waves were first explained for the case of St Paul's Cathedral by Lord Rayleigh, who revised a previous misconception that whispers could be heard across the dome but not at any intermediate position. He explained the phenomenon of travelling whispers with a series of secularly reflected sound rays making up chords of the circular gallery. Clinging to the walls, the sound should decay in intensity only as of the inverse of the distance rather than the inverse square as in the case of a point; source of sound radiating in all directions. This accounts for the whispers being audible all-round the gallery. Figure 4.5 below, gives an illustration of the movement of sound waves along the walls from the talker to the listener.

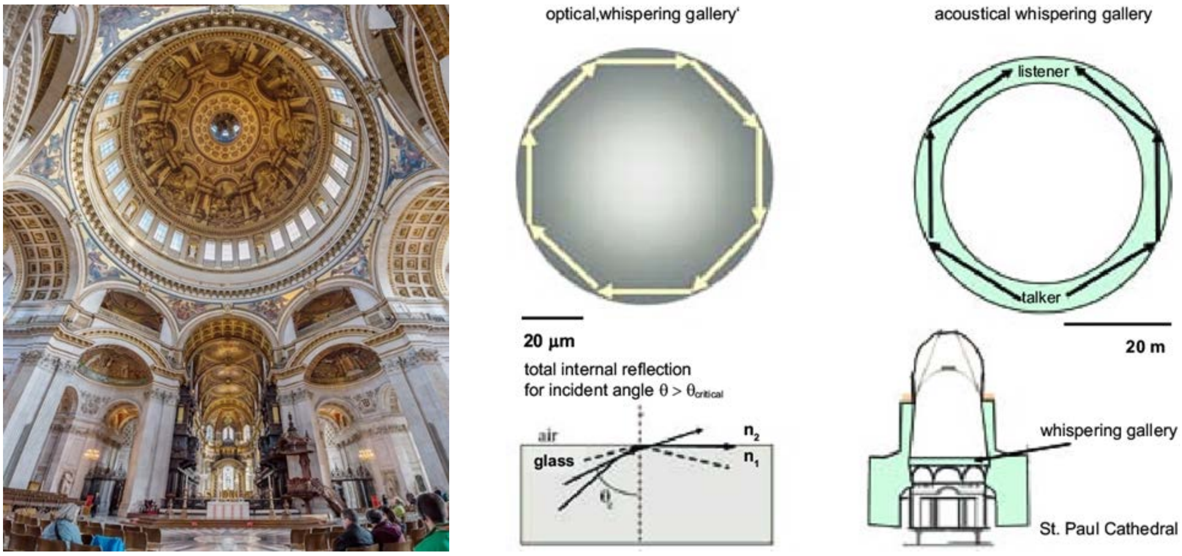

Figure 4.5: St Paul’s Cathedral whispering Gathering. (Yunzhi, 1985)

5.0 Building Forms and Acoustics

‘Sound exists in architecture and architecture exists in sound’. The process of how the two have influenced each other can be observed throughout history and has brought us the most surprising outcomes. (Joanna, et al., 2015)

Vitruvius, who, in his works, clearly states that a theatre has good acoustics, when dissonances or resonances are not present. While the words are heard clearly and in a pure tone, the famous author also stresses the fact that for the sound to possess appropriate characteristics, the area where the theatre is built should be chosen wisely. (Joanna, et al., 2015).

Sound waves striking an arbitrary surface are either reflected, transmitted or absorbed; the amount of energy going into reflection, transmission or absorption depends on acoustic properties of the surface. The reflected sound may be almost completely redirected by large flat surfaces or scattered by a diffused surface. When a considerable amount of the reflected sound is spatially and temporally scattered, this status is called a ‘diffuse reflection’, and the surface involved is often termed a ‘diffuser’. The absorbed sound may either be transmitted or dissipated. (Wikibooks, 2017). A simple schematic of surface-wave interactions is shown in figure 5.1 below. ‘A-ash color indicates sound absorption’ where most of the sound is absorbed and little is reflected. ‘B-black indicates sound reflection’ where all sound is reflected by the surface. ‘C-blue indicates sound Diffusion’ where the sound is scattered in a different direction.

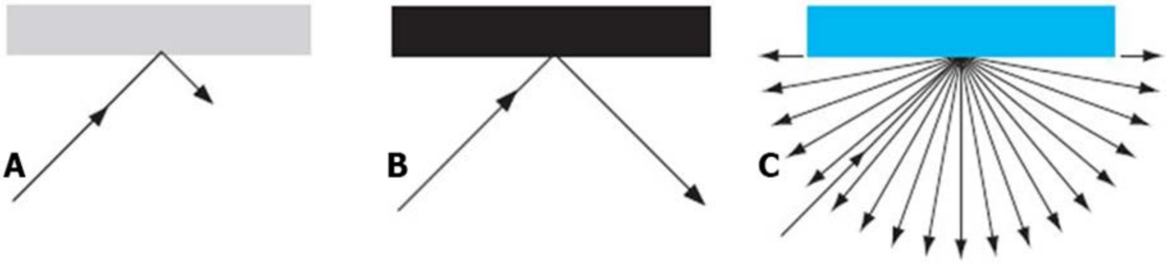

Figure 5.1 Surface-Sound interaction. Source: (Wikibooks, 2017)

For room acoustic geometry, all shapes and forms may be used if the architect and client so desire for specific purposes but not all shapes and forms are recommended especially for large gatherings due to poor distribution of sound and much work will be required to make the room sonically viable. This paper further reviews different room geometry and surfaces and their effect on the sound.

5.1 Convex and Concave Surfaces

As much as possible, a concave shape should be avoided for the surface. They cause sound reflections to converge at a focal point located at the geometric center of the curve or travel along the curve's surface which results in Loud hotspots within the space, or sound being carried an abnormally long distance. In most practical situations, such as in smaller spaces; sound concentration causes problems in speech intelligibility and music appreciation. Any time the surfaces of a room focus the sound which is reflected from them, they create spots of high intensity and other spots with low intensity. This is generally undesirable in an auditorium since you want a uniform, evenly dispersed sound to all listeners. If a concave shape must be used, a high absorbing material is needed to treat the surfaces and an acoustical consultant might also be able to help you adjust the geometry of your curve to minimize noise problems.

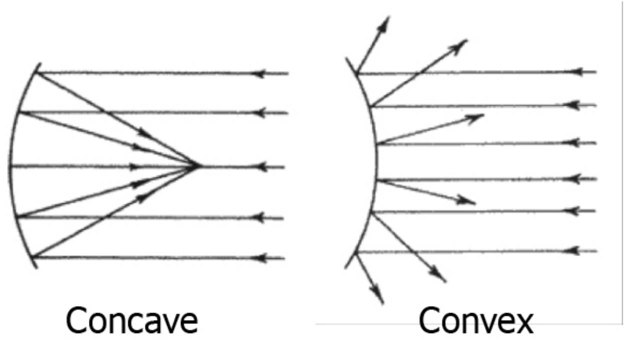

Figure 5.2 showing how sound reflects off a concave and convex surface. Source: (Avant acoustics, 2017)

5.2 Elliptical Enclosure

An ellipse has two focus points. Sound projected in any direction from one focus point, will travel to the other. Sound from any point will tend to be focused toward some point, so ellipses are certainly to be avoided for most acoustical purposes.

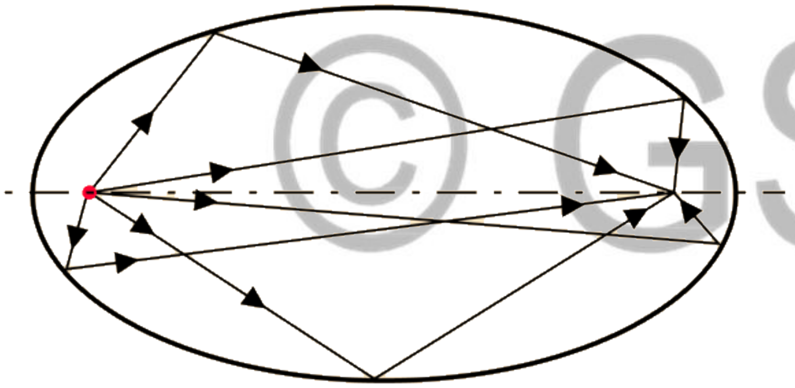

Figure 5.3 Movement of sound in an elliptical enclosure. Source: (Nave, 2006)

5.3 Parabolic Surfaces

All rays from the focus of a parabola to its surface will be directed outward as parallel rays. It is useful for projecting sound. Two parabolas as shown below can direct sound from the focus point of one to the focus point of the other with great efficiency. A microphone element can be placed at the focus point of a parabola and then aimed at a distant sound source. Parabolic microphones can pick up selected sounds at surprising distances.

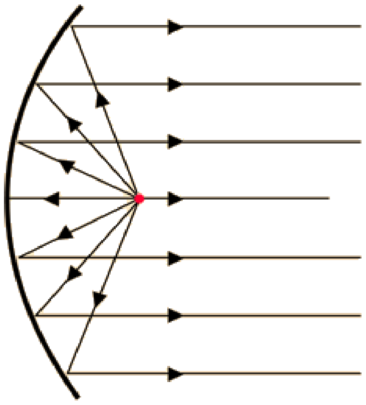

Figure 5.4: Reflection of sound in a parabolic surface. (Nave, 2006)

5.4 Dome, Sphere and Pyramid

These shapes have all the same issues as the sphere and cylinder but are even worse because of the concave ceiling. Again, without the addition of specific acoustic treatments, these shapes are nearly unusable for most public activities.

- If at all possible, never build a commercial space with a dome- or pyramid-shaped ceiling. This may look creative and artistic, but it will almost always result in a room that doesn't work well for good sound reproduction.
- If it must be done, be sure and include an acoustical consultant on your engineering team, and a budget for some "creative" acoustical treatment within the envelope of the dome or pyramid.

5.5 Cube

This is the worst of the realistically-usable room shapes. The problem is that all three dimensions are equal and that each of the three dimensions in parallel. Though it may not be obvious, a cube-shaped structure will result in all kinds of nasty sound problems if it has hard, reflective surfaces. Massive echo problems, and very-poorly distributed room modes, are the main issues with this shape. Much work will be required to make a cubed room sonically viable.

5.6 Shoebox Style

The shoebox shape is simply a rectangular room, typically with some balconies. Thus, the basic design is simple, but if not careful enough, this type of room can have problems with flutter echoes as explained in 4.3 of this research paper above. A well-known example of a shoebox concert hall is Musikverein in Vienna. It is generally agreed that the various structures in this specific room, such as the lateral statues, introduce scattering that helps to avoid the problem of flutter echoes.

Figure 5.5 Musikverein concert hall in Vienna source: (Odeon, 2020)

5.7 Fan Shaped Style

Fan-shaped rooms are perhaps the more common, as they can accommodate a large number of attendants while keeping a frontal view of the performers. At the same time, they are not prone to flutter echoes, simply because of the non-parallel walls. Additionally, the width of the room at the rear seats allows for good spaciousness of sound. Although not specifically a concert hall, an example of a fan-shaped room is the *Chaktomuk Conference Hall* in Cambodia.

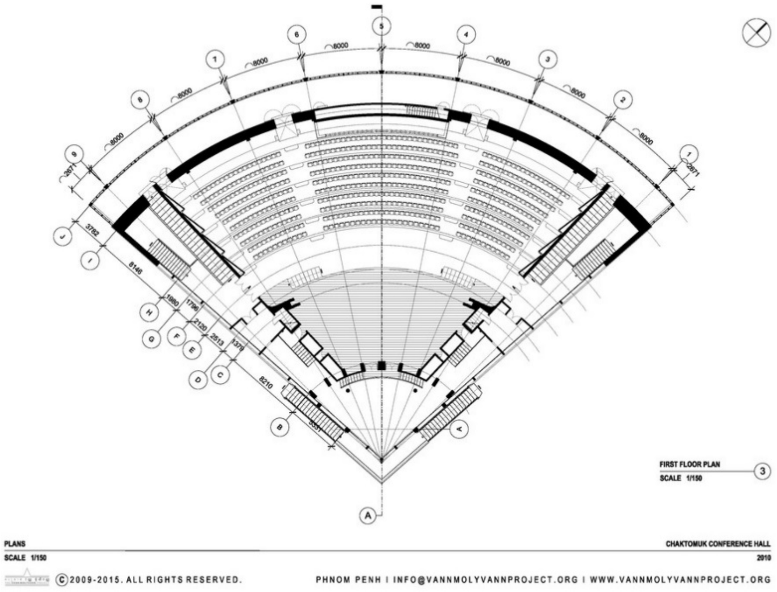

Figure 5.6 First floor plan of the Chaktomuk Conference Hall. Source: (Odeon, 2020)

5.8 Vineyard Style

Vineyard concert halls are named this way because the seating sections resemble slopes in a vineyard. This type of room has several advantages:

1. It is visually interesting.
2. The irregular pattern helps to avoid acoustic issues, such as flutter echoes and focusing.

The disadvantage, however, is that the design is very complicated and expensive. Examples of famous vineyard concert halls include the *DR Concert Hall* in Copenhagen, Denmark, the *Berlin Philharmonic's Concert hall* in Berlin, Germany and the *Philharmonie de Paris* in Amsterdam'

Figure 5.7 *DR Concert Hall* in Copenhagen, Denmark. Source: (Odeon, 2020)

6.0 Conclusion and Recommendation

'Sound is not a tangible thing, it is a transformative experience' (Michael Fay, 2013). Good acoustics are linked to human well-being. It is a question of whether you feel comfortable in the acoustic environment, whether it is at home, in a restaurant, at a concert, in the theatre or wherever. According to classic acoustics theory, there are five requirements which, when met, result in good acoustics:

- An appropriate reverberation time
- Uniform sound distribution
- An appropriate sound level
- An appropriately low background noise
- No echo or flutter echo

The various shapes, forms and concept of Acoustics as illustrated and explained in this research work, clearly explains the effects of building forms on Acoustics. Therefore, Concert halls, Auditoriums, Lecture Halls, Worship centres and any interior space involving performances with Audience more than 10 persons, must consider Acoustics as a functional requirement. The building form should be designed in such a way that the audience will be close to the sound source and free from noise as much as possible. As clearly explained in 4.5 and 4.6 of this Article the difference between 'room Acoustics' and building' Acoustic', Building Designers should ensure that both the interior and exterior of the space considered, should be well treated with the right materials and install the right sound equipments.

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