Acoustic Control in A Multipurpose Hall: The Case Study of LaLa Mustafa Pasa Sports Complex, Eastern Mediterranean University, Gazimağusa-North Cyprus

Timothy Onosahwo Iyendo

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Prof. Dr. Elvan Yılmaz
Director

I certify that this thesis satisfies the requirements of thesis for the degree of Master of Science in Architecture.

Assoc. Prof. Dr. Özgür Dinçyürek
Chair, Department of Architecture

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Architecture.

Prof. Dr. Mesut B. Özdeniz
Supervisor

Examining Committee

1. Prof. Dr. Mesut B. Özdeniz

2. Asst. Prof. Dr. Halil Zafer Alibaba

3. Asst. Prof. Dr. Polat Hançer

ABSTRACT

In recent years, due to tight budgets, a large number of multipurpose halls have been constructed applying relatively inexpensive materials without regard to planning for noise control to mitigate loud, unpleasant, unanticipated, or undesired sound. Consequently, after construction is completed, noise issues are often proven within the spaces and render the initial purposes of the structure unattainable. In this study both qualitative and quantitative research methods are used to identify the acoustics problems, its sources, effects, and control. The research revealed that the Rapid Speech Transmission Index [RASTI] and Reverberation Time [RT] of the Hall was 0.34 and around 4.5 seconds respectively, which indicated that EMU, LaLa Mustafa Pasa Hall in North Cyprus is having speech intelligibility and echo problems. The study would not only edify potentials and professionals on the importance of acoustics as a major factor in building design, but also address the common solutions to resolve noise in multipurpose spaces. This multipurpose hall is expected to be used for various activities such as music functions, sports and speeches. Against this background the study highlights the fundamentals of sound and room acoustics including noise from interior and exterior sources as well as looking into the possible economic solutions that can be taken within the building to attenuate noise. Suggestions and recommendations to this effect are given at the end of this research to guide any institution or company and all those who may wish to build a proficient and acceptable multipurpose hall in the future.

Keywords: Acoustic Control, Room Acoustics, Multipurpose Halls, Reverberation Time, Echo, Speech Intelligibility.

ÖZ

Son yıllarda düşük bütçeler nedeniyle, birçok çok amaçlı salon, ucuz malzemeler kullanılarak ve ses kontrolu yapılmadan inşa edilmektrdic. Bunun sonucu olarak, yapılar inşa edildikten sonra birçok akustik sorunlarla karşılaşmakta ve amacına hizmet edememektedir. Bu çalışmada niteliksel ve niceliksel araştırma yöntemleri kullanılarak, akustik sorunları tanımlamak, bunların kaynaklarını, etkilerini ve çözüm yollarını bulmak amaçlanmıştır. Araştırma göstermiştir ki hızlı konuşma iletim endeksi [RASTI] ve Çınlama Süresi [RT] sıasıyla 0.34 ve 4.5 saniye dolayındadır. Bu da Doğu Akdeniz Üniversitesi DAU LaLa Mustafa Pasa Salonunda, konuşma analaşılabilirliğinin çok düşük olduğunu ve istenmeyen yankıların bulunduğunu göstermektedir. Çalışma yalnız profesyonelleri yapı tasarımında akustiğin önemi konusunda yalniz profesyonelleri değil, çok amaçlı salonlarda bu sorunların nasil basit olarak çözülebileceği konusunda gili herkesi aydınlatmayı amaçlamaktadır. Bu çok amaçlı salon sporun yanısıra, muzik, konuşma ve gösteri amaçlarına da hizmet etmektedir. Bu nedenle çalışma sesin temelini, iç ve dış gürültü sorununu, oda akustiğini, muhtemel ekonomik çözümleri ele almaktadır. Tezin sonunda verilen tavsiler ve öneriler, gelecekte çok amaçlı salon tasarlayıcılarına yol gösterecektir.

Anahtar Kelimeler: Akustik kontrol, Oda Akustiği, Çok Amaçlı Salonlar, Çınlama Süresi, Yankı, Konuşma Anlaşılabilirliği

To my family and the Almighty Jehovah God who kept me alive to this very moment and who has been a source of strength and zeal, enabling me to successfully cope with the challenges of both this programme and my life itself.

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I finally give all glory to the **Almighty God Jehovah**, the sustenan of my life and giver of knowledge in Jesus name…………..Amen.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF SYMBOLS AND ABBREVIATIONS

%ALc	Percentage Loss of Consonants
f_0	Frequency Resonance
C_{te}	Linear Early-To-Late Ratio
E_{BL}	Background Energy
E_{SL}	Speech Energy
E_e	Relative Energy
E_1	Late Energy
U_{te}	Useful-To-Detrimental Ratio
g	Lambda
m’(F)	Modulation Index
t_e	Early Time Limit
$\propto$	Absorption Coefficient/Fraction Of Energy
$\approx$	Approximately
µbar	Microbar
µPa	Micropascal
µW	Microwatt
AC	Arcticulation Class
AI	Articulation Index
ANSI	American National Standards Institude
ASHA	American Speech-Language-Hearing Association
ASHRAE	American Society Of Heating, Refrigerating And Air-Conditioning Engineer

ASTM	American Society For Testing And Materials Standards
L.M.P.S.C	LaLa Mustafa Pasha Sport Complex
π	Pii
c	Speed of Sound
V	Volume
lb	Pound-Mass
ra	Relative Amplitude
rms	Root Mean Square
G[i]	Weighing Factors
BR	Bass Ratio
DIRAC	Direct Iterative Relativistic All-electron Cclculation
MPF	Modulation Transfer Function
RAST	Rapid Speech Tranmission Index
BL	Background Level
C80	Early to late index or Clarity
Cps	Cycles Per Second
D/R	Direct To Reverberant
Db	Decibel
EDT	Early Decay Time
f	Frequency
Ft	Feet
Ft^2	Feet Square
HVAC	Heating, Ventilation And Air-Conditioning
Hz	Hertz
I	Intensity Of Displacement

IIC	Impact İnsulation Class
INR	Impulse Response To Noise Ration
In	Inch
Kg	Kilogram
L	Length
L_{NA}	A- Weighted Long-Term Average Level Background Noise
L_{SA}	A- Weighted Long-Term Average Level
M	Metre
m^2	Metre Square
m^3	Metre Cube
Max.	Maximun
mm	Milimetres
msec	MiliSecond
mW	Miliwatt
N	Newton
NC	Noise Criterial
P_0	Threshold of Human Hearing
Pa	Pascal
PA	Public Address
PNC	Prefered Noise Criterion
Pt	Point
PTS	Permanent Threshold Shift
r^2	Redius Square
Rc	Room Criterial
RT	Reverberation Time

R_w	Weighted Sound Reduction Index
s	Seconds
S	Emitted Sond Power
SI	Speech Index
SIL	Speech Interference Level
SL	Speech Level
SNR (S/N)	Sıgnal-To-Noıse Ratıo
SPL	Sound Pressure Level
Sq	Square
STC	Sound Transmission Clss
STL	Sound Transmission Loss
t	Time
TL	Transmission Loss
TTS	Temporary Threshold Shift
v	Speed Or Velocity of Sound

Chapter 1

INTRODUCTION

1.1 Background of the study

According to science and engineering encyclopedia of 2001, “acoustics (Greek word derived from ***“akouein”*** *to* hear), is a general term used for the scientific discipline of sound”. Harris (1975), simply defined acoustics “as the science of sound, including its production, transmission, reception, and effects”. On the other side, Merriam Webster online dictionary defined “acoustics as the science that deals with the production, transmission, reception, effects and control of sound” (www.physic.byu.edu). In other words, “acoustics can be defined as the branch of science that deals with room acoustic and noise control” (Harris, 1994).

Means (2009), states that “architectural acoustics deals with the construction of enclosed or within a single area (i.e. reflection, reverberation, absorption, transmission etc.), so as to enhance the hearing of speech or music”. Funk and Wagnalls (1994), state that “building acoustics was unexploited aspect of the study of sound until relatively recent times”. “Marcus Pollio, a Roman architect who lived during the 1st century B.C, made some pertinent observations on the subject (acoustics) and came out with some astute guesses concerning reverberation and interference” (Barron, 2003).

The scientific aspects of this subject, however, was comprehensively first treated by an American physicist Joseph Henry in 1856 and was ameliorated in full by Wallace Sabine an American physicist in 1900 (Funk and Wagnalls, 1994).

Reports gathered over the years; show that we are living in a noisy environment. Noise can scotch or thwart speech communication, and can also be a physical health peril as well. Rogers (1982), confirms that the brain pressure is often increased as much as 400 percent by sudden loud noise, which may cause loss of temper, incitement, and permanent hearing loss. Humans are usually annoyed by noise and react to it. Due to this cause, the need to achieve noiseless conditions in offices, factories and multipurpose dwelling housing is considered to provide greater comfort for the occupants of these buildings (Harris, 1994).

Acoustic consideration is essential to the functionality of almost every type of buildings, from residential buildings, open offices, worship centers and multipurpose halls. Thus, the concept of habitability within the framework of architectural practices for a functional room space means more than just normal conventional design consideration (i.e. Lighting, ventilation etc.). However, the functionality of a multipurpose space will not be complete, without due consideration of the sound production (acoustics) of the space. The effect of both indoor and outdoor generated sound must be considered to enhance an acoustic ideal environment for its users. Thus, shelter can only fulfill its requirement as a functional space, if noise reduction is taken as one of the design consideration for a habitable space, especially with regards to multipurpose spaces since attaining noiseless conditions in such spaces are almost impossible.

The consideration of acoustic in building design is a major factor often undermined and this relatively reduces the functionality of buildings as noise has quite a number of adverse effects on humans, such as discomfort and health related problems which reduces the overall productivity of humans. Therefore, accounting for acoustic conditions can greatly increase the overall comfort quality of a space, whereas poor acoustics upshot in an unhealthy and dangerous environment.

In multipurpose spaces, acoustic consideration is a factor to ameliorate on good listening condition as background noise, reverberation (echo), air born sounds, structure-born sound and speech intelligibility are some of the acoustic problems of most auditoria, halls or multipurpose spaces which reduces the acoustic stability of the entire building.

Hunt (1978), avers that acoustics is associated with music, and it has been a field of concern for many centuries. Rayleigh (1945), also averred that Pythagoras was the first Greek philosopher credited to carry out studies on the physical origin of musical sounds around 550BC. In Pythagoras's experiment, he ascertained that "when two strings on a musical instrument are struck, the shorter one will emit a higher pitched sound than the longer one". Approximately in 240 BC, Crysippus a Greek philosopher postulated that "sound was generated by vibration of parts of the musical instrument" (the strings, for example), he also stated that " sound was transmitted by means of vibration of the air or other fluid, and that this motion caused the sensation of hearing when the waves strike a person's ear " (Rayleigh, 1945).

Many other scientists made further assertions and contributed to the issue of acoustics being associated with music sound. Galileo Galilei an Italian physicist, famously known as the father of modern science also contributed to study of music sound, which led to his published discussion in 1638, on the vibration of strings in which he developed quantitative relationships between the frequency of vibration of the string, the length , its tension, and density of the string (Finocchiaro, 1989).

Another school of thought came from Otto Von Guericke, who affirms that he "doubted sound was transmitted by the vibratory motion of air, because sound was transmitted better when the air was still than when there was a breeze". Guericke concluded that air was not necessary for the transmission of sound (Raichel, 2006).

Further research was conducted by Sir Isaac Newton in 1687; he compared the transmission of sound and motion of waves on water surface. As well, he developed an expression for the speed of sound based on the premise that the sound wave was transmitted isothermally, whereas sound is emitted adiabatically for small amplitude sound waves, by analogy with the vibration of a pendulum. Various contemporary researchers came out with various results although with little similarity in their research. This was still on when Rayleigh published a two-volume work in 1877, "The theory of sound", which placed the discipline acoustics on a solid scientific foundation (Barron, 2003). Within the interval of 1898 and 1900, Sabine wrote and produced series of written document on reflection of sound in rooms where he introduced the cornerstone of architectural acoustics (Sabine, 1922).

In 1827, a British physicist Sir Charles Wheatstone, invented the famous Wheatstone bridge, he produced an instrument similar to the stethoscope, which he called a ‘‘microphone ’’. Subsequently the invention of the triode vacuum tube in 1907 and the initial advancement of radio broadcasting in the 1920s, electric microphones and loudspeakers were manufactured. Research was also carried out on the concepts pertaining to loudness and the reaction of the human ear to sound in the 1920s (Barron, 2003).

Between 1930 and 1940, mark the beginning of noise control principles application to buildings, automobiles, aircraft and ships, and from their researchers began to investigate the physical processes involved in sound absorption by porous acoustic materials. “With the advent of World War II, improvement on the ways in which speech communication problems could be solved in noisy surroundings, such as in tanks and aircraft were made”. “Subsequently, after World War II more pragmatic and rigorous research in noise control and acoustics was undertaken in several scientific institutes and universities, which gave rise to addressing noise problems in both architecture and industry properly in post war time period” (Beranek, 1962).

Afterwards, research was also conducted to solve noise problems in residential buildings, workplace and transportation. “The adjustment of the (Walsh–Healy Act) in 1969 contributed greatly to the control of noise activity in the industry and the law demanded that the noise exposure of workers in the industrial environment be reduced to a specific value (90 dBA for an 8- hour period)”. “The law also avers that, workers should be provided and trained on how to use personal hearing protection devices, if noise exposure exceeds prevented level” (Barron, 2003).

1.2 Statement of the problem

The consideration of acoustic in building design is a major factor that is often undermined and this relatively reduces the functionality of the building and the overall productivity of the users as well.

Thus, accounting for acoustic situations can greatly increase the overall comfort level of the entire space, whereas poor acoustics can result in unsafe and insalubrious environment. Against this background, acoustic consideration is a major factor to be considered in LaLa Mustafa Pasa multipurpose hall to enhance good listening condition since reverberation (echo), background noise and speech intelligibility are the major acoustic defects of the space and which reduces the acoustical suitability of the building as a whole.

1.3 Research aim and objectives

(a) Aim

The aim of this research study is to investigate the acoustic (noise) problems in LaLa Mustafa Pasa multipurpose sports complex, Eastern Mediterranean University North Cyprus.

(b) Research Objectives

This research survey is geared towards examining the noise issues in LaLa Mustafa Pasa Multipurpose hall, Eastern Mediterranean University with the view:

1. To identify the possible existing acoustic problems.
2. To analyze the existing problems identified.
3. To determine the most economic solutions to the problems that can be taken within the sport complex to enhance a comfortable good listening environment for its users.

1.4 Research questions

In order to critically examine the impact of noise in LaLa Mustafa Pasa Multipurpose Sports Complex (Eastern Mediterranean University), this research study provides answers to the following three (3) objectives of the research work.

1. What are the ways to identify the possible existing acoustic problems?
2. What appropriate method is to be used to analyze the problems identified?
3. What parameter that could be used to determine the most economic solutions to the problems that can be taken within the sport complex to enhance a comfortable good listening environment for its users?

1.5 Scope of the study

This study based its scope on the noise (acoustic) problems and control of LaLa Mustafa Pasa Multipurpose Sport Complex (Eastern Mediterranean University-Gazimağusa, North Cyprus).

1.6 Limitation of the study

The issue of insufficient equipments, time constraint, insufficient income, and the unavailability of multipurpose spaces in Gazimagusa, Northern-Cyprus pose a major limitation on this research.

1.7 Significance of the study

This study is expected to contribute to the body of knowledge by acquitting both practicing and potential designers and architects with appropriate modern design strategies and the relevant options needed to effectively control and manage the behaviour of sound within multipurpose spaces.

The research will be appealing to students of Architecture, urban planning, civil engineering and also serve as a reference document to those who may carry out similar study on the topic or related topic. Other beneficiaries will be any government ministries and research institutions/organizations who may find it helpful for the furtherance of planning and development of auditorium/Hall or multipurpose spaces.

1.8 Definitions of commonly used technical terms in noise control

Acoustic environment: This is the overall environment, including the exterior to interior that affects the acoustic conditions of the space or structure under consideration.

Amplification: the increase in intensity level of an audible signal produced by means of a loudspeaker and is associated with electric amplification apparatus.

Attenuation: The decrease in level of sound, usually from absorption, divergence, scattering, or the cancellation of the sound waves.

Audible sound: Acoustic oscillations of such a character as to be capable of giving rise to the sensation of hearing.

Distortion: This is known as any change in the transmitted sound signal such that the received is not a faithful replica of the original source sound.

Flanking path: A path along which sound is communicated that leads to flanking sound transmission.

Frequency analyzer: This is an instrument used for measuring the acoustic energy present in various frequency subdivision, for instance (one, one-third, one-tenth-octave bands etc.) of a complex sound.

Velocity of sound: This known as the rate at which a sound wave travels from a source through a medium to the listener or receiver and the SI unit is in m/s.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

“The problem of achieving good hall acoustics has induced much valuable research since 1950” (Barron, 2009). Ryan, (1998) avers that is easier to achieve good acoustics in smaller halls than in larger ones. Many of these old halls suffer from deficiencies at certain location, particularly from poor sightlines in the side balconies, for example the *Grosser Musikvereinssaal, Vienna* (Bradley, 1991), as shown in appendix A: plate 1. Designing auditoria is a complex, elaborate but highly constrained exercise. All auditoria rely on both visual and acoustic stimulation (Brewer, 1854: Barron, 2009). The discussion of auditorium design and development on the basis of precedent were well established in Brewer’s day, even if not on a particular scientific base. Vitruvius, (1960) based his geometric prescriptions for designing Greek and Roman theatres on an understanding of acoustics. Over the years, the fan shaped plan and arena form became highly developed and remain a constant point of reference for present design at that time. The developments of these dominant auditorium plans through the centuries were really fascinating (Barron, 1992). The first of the fan shape design was the *Dumon’t Parrallele De Plans des Plus Belles Salles De Spectacles* of 1774. Dumont proposed his own designs with vast concave domed ceilings, which would not give any acoustician nightmares (Barron, 1993).

In the late 19th century, European theatres and opera houses experienced a building rapid growth. By 1896 Sachs could fill his monumental three-volume modern opera houses and theatres with extensive details about more than 50 theatres completed since Contant's earlier survey (Barron, 2009). Beranek (1962), pioneered analysis of auditorium acoustics on the basis of several independent subjective qualities, such as 'intimacy', 'liveness' and 'warmth'. He was the first person to give a serious attempt on the complete explanation of auditorium acoustics and to answer many misconceptions on acoustics as a subject. Patte (1782), was another fellow who first made attempts pertaining to auditorium form and acoustics behaviour by proposing elliptical plans. Attempts were also made by Saunders (1790), by proposing circular auditorium, although such forms can be dangerous due to focusing by concave surfaces. Dr Reid in 1835, also made some progress in understanding the acoustics of rooms in the nineteenth centuries by postulating that "any difficulty in the communication of sound in large rooms arises generally from the interruption of sound produced by a prolonged reverberation" (Barron, 1993). Dr Rein also successfully gave advice on the acoustic treatment of the Westminster contemporary House of Commons (Bagenal and Wood, 1931).

Around 1900, it was discovered that many large playhouse (theatre) were built at that time and are still in use, which still function and have good acoustics. On the other hand, Roger Smith summarizes the state of art in 1861 but fail to reconcile the conflicting evidence from the men of science (Smith, 1861). Lord Rayleigh (1878), also postulated on room acoustics in his book "theory of sound", and which is still widely used today by scholars and researchers.

Sabine (1922), discovered a solution to the acoustics of the newly *Fogg Art museum lecture room*, as shown in appendix B: plate 2. In his research, he realized that there was too much reverberation in the lecture room; he measured the unoccupied reverberation as 5.5 seconds and later developed a technique for measuring the decay time of residual sound after an organ pipe was switched off. He achieved that by ear observation and stop watch. Modification was made to ameliorate the acoustics of the lecture room in 1898 and was finally demolished in 1973 (Cavanaugh and Wilkes, 1999).

In appendix C: plate 3, is another outstanding hall, the *Boston music Hall* of 1863, which was completed in the fall of 1898, and Sabine was ask to evaluate the acoustic issues of the hall (Beranek, 1979). "Sabine later discovered that the reverberation time was proportional to the reciprocal of the amount of absorption, which is now called the Boston symphony hall, a concert hall that has gained a reputation for having one of the best acoustics worldwide" (Sabine, 1922). In his paper of 1898, Sabine summarized the requirements for room acoustics as:

> *"In order that hearing may be good in any auditorium, it is necessary that the sound should be sufficiently loud; that the simultaneous components of a complex sound should maintain their proper relative intensities; and that the successive sounds in rapidly moving articulation, either of speech or music, should be clear and distinct, free from each other and from extraneous noises. These three are necessary, as they are the entirely sufficient, conditions for good hearing"* (Sabine, 1922: Barron, 2009).

Barron (2009), in his book auditorium acoustics and architectural design, he stated that the *Royal Festival Hall*, London, of 1951 was a typical of several subsequent dashing hopes due to the lack of proper acoustic consideration, see appendix D: plate 4. Table 2.1, shows a brief and comprehensive overview of some British hall chronologically. Cremer and Muller (1982), made progress in terms of measurable quantities, which are now widely used for music listening. Meyer (2009), recently, takes it as the basis characteristics of musical instruments (spectral, directional etc) and how this is significant for performance.

Arthur (2002), made some study on British auditoria between 1982 and 1983, which led to measurement of acoustics in over 40 auditoria in which subjective test were conducted with listeners completing questionnaire at public performances. Also, five British auditoria which were completed since 1990 were tested and reported as well. The new scientific basis for auditorium acoustics has made acoustics design more confident exercise over the years, in spaces for both music and speech (Talaske et al., 1982).

According to Barron (1998) in his research on Royal Festival Hall acoustic of 1951, he stated that “to design a concert hall is to go down into the arena and risk death from violence of your contending passions”. The London examples at *Vaux Hall and Ranelagh Gardens* were copied in several other European cities, but none of these old London concert venues survived the test of time, though they are well documented (Forsyth, 1985), as shown in appendix E: plate 5. A technical analysis of the three of these halls that survived has been made by (Bradley, 1991). While the years progress, many other rectangular halls were also built which gained good standing, among them are the Liverpool Philharmonic Hall of 1849-1933, the

Stadtcasino, Basel of 1876, the St Andrew's Hall, Glasgow of 1877-1962 and the Grosser Tonhallesaal, Zurich 1895. Their acoustic character was similar to their contemporaries (Barron, 1998).

Table. 2.1: Basic details of 16 British concert halls

Hall	**Date**	**Seats**	**Auditorium volume (m^3)**	**Reverb. Time (s)**	**Acoustics consultant**
Royer Albert hall, London	1871	5090	86650	2.4	–
Usher Hall, Edinburgh	1914	2217-333	16000	1.7	–
Philharmonic Hall, Liverpool	1939	1767-184	13560	1.55	H. Bagenal
Watford Colosseum	1940	1586	11600	1.45	H. Bagenal
Royal festival Hall London	1951	2645-256	21950	1.45	H. Bagenal, P.H. Parkin and W.A Allen
Colston hall, Bristol	1951	1940-182	13450	1.7	"H.R Humphreys, P.H. Parkin and W.A Allen"
Free trade hall, Manchester	1951-1996	2529	15430	1.55	H. Bagenal
Fairfield hall, Croydon	1962	1539-250	15400	1.6*	H. Bagenal
Lighthouse concert hall, Poole	1978	1473-120	12430	1.55*	P.H. Parkin
Barbican concert hall, London	1982	2026	17750	1.6	H. Creighton
St David's hall, Cardiff	1982	1687+270	22000	1.95	Standy Brown Associates
Royal concert hall, Nottingham	1982	2315+186	17750	1.75*	Artec Consultants Inc.
Glasgow royal concert hall	1990	2195+263	28700	1.75	Fleming and Barron with Sandy Brown Associates
Symphony hall, Birmingham	1991	1990+221	25000	1.85	Artec Consultants Inc.
Bridgewater hall, Manchester	1996	2127+276	25050	2.00	Arup Acoustics
Waterfront hall, Belfast	1997	2039+195	30800	1.95	Standy Brown Associates

Source: (Barron, 2009-Auditorium Acoustics and Architectural Design)

In table 2.1 above, the cited reverberation times are mean occupied values at 500/1000Hz (* is predicted from unoccupied measurement).

In 1870, the Gesellschaft der Musikfreunde opened a new building adjacent to the Ringstrasse, which comprises a Grosser and Kleiner Musikvereinssaal and was designed by architects Theophil Ritter Von Hansen (Barron, 2009). The hall was renamed at a later date and was called the *Brahmssaal*, while the former has established the esteem as having one of the best acoustics in the world. The hall differs in several respects from the original design and was renovated as a result of fire safety in 1911. Although clement still records some lapses on acoustics issues in the *Grosser Musikvereinssaal Hall***.** See appendix A: plate 1. He discovered that lateral reflections were the major problems of the hall (Clements, 1999). Table 2.2 shows details of some renowned classical concert halls.

Appendix F: plate 6 shows the Boston *symphony Hall*, Massachusetts, was rated as one of the best in the 18th century. Beranek who was conversant with the hall, delineated the sound in the hall as clear, live, brilliant and loud (Beranek, 2004). Muller (1992) verified that the certainty of the hall is not based on single feature to have a satisfactory acoustics in the hall. The reverberation and envelopment produced by the sound were confirmed to be very good. Bradley (1991) discovered that there are a few audible differences between the halls, some of which can be connected or linked to measurements.

Modern movement in architecture after First World War marked the end of decorative mouldings', the statues in niches and coffered ceilings of the classical halls. After this era, architects Auburtin, Granet and Mathon, designed *Salle Pleyel* of 1927, Paris (Barron, 2009). See appendix G: plate 7. Andrade (1932), in his research on this particular hall recorded that he experienced a clear hearing throughout the lecture hall, including the back gallery which is more than 45 metres away from the performance stage. These are claims which the classical halls could not attain. A loud clear sound was achieved but at the expense of most other aspects considered important for music listening. The hall was renovated in 1981, 1994 and 2006 by Arctec consultants of New York, involving major revision of the stage area, extending the balconies along side walls and also reducing the seat capacity by 500 seats, raising the ceiling as well for to attain better acoustics (Barron, 2009).

Table. 2.2: Details of four (4) most renowned classical concert halls

	Concert Hall			
	Grosser Musikvereinsaal, Vienna	**Neues Gewandhaus, Leipzig**	**Concertgebouw, Amsterdam**	**Symphony Hall, Boston**
Date	1870	1884-1944	1888	1900
Volume (m^3)	15000	10600	18770	18750
Seat capacity	1680	1560	2037	2625
Length (m)	52.9	44.9	43.0	50.7
Width (m)	19.8	19.2	28.4	22.9
Height (m)	17.8	15.1	17.4	18.8
Reverberation time (s)	2.0	1.55	2.0	1.85

Source: (Beranek, 2004: Baron, 2009)

Appendix H: plate 8 shows another prominent hall, which was of interest, the *Alberta Jubilee* halls in Canada with 2700 seats and was refurbished in 2005 by Fred Valentine a Canadian architect together with other North American consultants and the Danish acoustical company Jordan Akustic to attain good acoustics in the halls. Their major modification was that the seating sections were raised next to the side walls, thereby creating reverse-splay seating areas rather than fan shape (Jordan and Rindel, 2006).

Meyer and kuttruf (1959) were other acousticians who gave advice on how to improve the acoustics of *Beethovenhalle* in Bonn of 1959, see appendix I: plate 9, and was designed by Architect S. Wolske. Their advice on this hall was to place diffusing elements on the whole or part of the ceiling or walls to avoid corner reflections and sound focusing. After the application of acoustics treatment, it was discovered that the hall has one of the explicit instances of substantial acoustic scattering treatment, which made (Beranek, 1962) to rate the acoustics of the hall as 'Good' with 1420 seats and internal volume of $16000\,\mathrm{m}^3$ (Beranek, 1962: Barron, 2009).

During the post-war construction period, *Berlin Phiharmonie Hall* of 1963 designed by architect Hans scharoun between 1893-1972, in collaboration with acoustician Lothar Cremer between 1905-1990 and sprang out as one of the notable Halls at that time (Cavanaugh and Wilkes, 1999). See appendix J: plate 10. In 1956, the hall won the design competition (Barron, 2003). In this particular hall, Cremer was just concerned about the acoustic condition of the orchestra by making it reflect like those of the other halls. The hall surfaces are as much as 3m high and surrounded by the stage, the ceiling above the stage of the hall was suspended reflecting panels to absorb acoustics. "The reverberation time of the hall was deliberated to be 2.1 seconds at 125Hz when fully occupied" (Cremer, 1989).

In the 1980s, many other spectacular halls sprang up, among such are the *Roy Thomson hall* in Toronto, designed by Erickson. See appendix K: plate 11. The gross plan of the hall is roughly circular in shape with a bicycle wheel construction supporting the ceiling which based on a hub above the stage front. Such circular or concave plan can result to rigorous focusing situations but was addressed by substantial segmentation of the walls. In 1978, tilted reflectors were introduced around the side walls to ameliorate the early lateral reflections. The overstage panels were originally 2.1m diameter convex circular ‘saucers’ made of clear acrylic plastic, covering 40 percent of the stage area. These reflecting panels were orientate to serve the stage, main floor and the first balcony and the reverberation time in fully occupied situation was about 1.8 seconds which can be reduced to 1.4 seconds (Barron, 2009). “The hall was renovated in 2002 due to criticisms of the acoustics by architect Alison Rose in collaboration with Thomas Payne of Kuwabara, Payne McKenna Blumberg (KPMB) Architects and Russell Johnson of Artec Consultants Inc” (Alison, 2009).

Appendix L: plate 12 portrays *Suntory Hall* in Tokyo of 1986 which was also an influential Hall that gained prominence and the acoustics was work upon by Nagata acoustics consultant. The roof profile of this hall in long section is having similar characteristics with that of phiharmonie of Berlin, having a resemblance of a tent. The seat capacity is found to be 2006, with a volume of 21000 m^3 and a mid-frequency reverberation time of 2.0 seconds (Harris, 2001).

Metkemeijer et al, (1998) recorded that in 1987 a modern rectangle hall was built in Hague and this hall is known as the *Dr Anton Philips Hall* with seat capacity of 1900 with a single balcony which goes round all the four walls of the hall and severs as a low-budget solution. According to (Harris, 2001) “he confirms that the walls are made up of damped steel panels profile to provide scattering and the profiling consists of different-depth slots in both the horizontal and the vertical direction”.

The *McDermott Concert Hall* in Dallas of 1989 was recorded by (Cavanaugh and Wilkes, 1999) as the first of a continuing series of parallel-sided hall designed by

Artec. The hall consists of about 2065 seats with a chamber volume of 7200 m^3, 30 percent of the auditorium. See appendix M: plate 13. An example of a hall with terrace is the *Kitara Concert Hall* of 1997 in Sapporo, Japan with Nagata acoustics as the acoustics consultant. In this hall, the introduction of large convex surface common to ameliorate sound and the hall was flexible as well (Beranek, 2004).

From the selected Halls studied in the literature review of both early and recent Halls, in this thesis shows that reverberation time has always been a major problem in halls either large or small.

2.2 The physical characteristics of sound

The attribute or features of sound that can be detected by the human ear comprises the followings:

1. **Frequency**: “The frequency of a sound wave is simply the number of complete vibrations occurring per unit of time and it is measured in decibels (dB)” (Cavanaugh and Wilkes, 1999). “The decibel scale is a logarithmic scale based on the logarithm of the ratio of a sound pressure to a reference sound pressure (the threshold of audibility), while the frequency of sound waves is measured in Hert$_z$ (H$_Z$, also known as cycles per second) and grouped into octaves (an octave band is labeled by its geometric center frequency). Human hearing is most acute in the 1000 to 4000 H$_Z$ octave bands” (Binggeli and Greichen, 2011). Table 2.3 shows the recommended centre frequencies and the band limits of eight octave band in common use.

Table. 2.3: Octave band frequency

Approximate band limits (H_Z)	**Octave-band center frequency (H_Z)**
22 – 44	31.5
44 – 88	63
88 – 175	125
175 – 350	250
350 – 700	500
700 – 1400	1000
1400 – 2800	2000
2800 – 5600	4000
5600 – 11,200	8000

Source: (Ramsey et al, 2000- Architectural Graphics Standard)

2. **The wavelength of sound**: “This is the perpendicular distance between the maxima two successive wavefronts at a given instant time”. It is measured in metres (m) and represented with the Greek alphabet ‘γ’ (lambda). The wavelength of a sound is related to frequency (f) in Hertz and the speed of sound (v) in meter per second, and is denoted mathematically by:

$$\lambda = \frac{v}{f}$$

For convenience, the relationship between frequency of a sound and wavelength is given graphically as in figure 2.1.

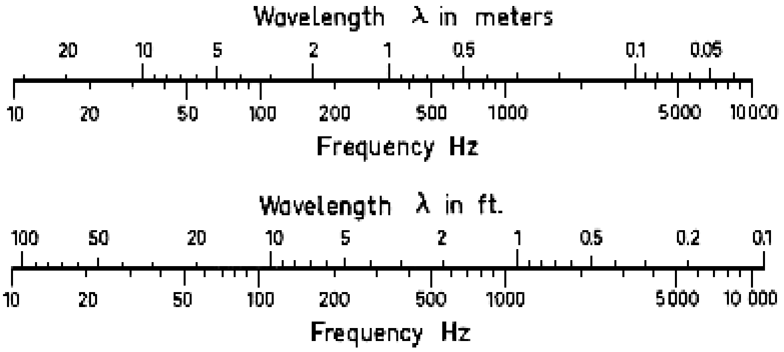


Fig. 2.1: Relationship between frequency f and wavelength λ of sound in air

(Source: Harris, 1994)

3. **Period**: This simply means the time taken for one complete cycle or oscillation, denoted by capital letter 'T' and measured in seconds (s).
4. **Amplitude**: We perceive amplitude as volume and this is known as the maximum displacement a wave travels from the normal or zero position, as shown in figure 2.2. This distance corresponds to the level of motion in the air molecules of a wave. "As the level of motion in the molecules increases, its strike the ear drums with greater force progressively and as a result causes the ear to react to a louder sound". "The amplitude of a sound wave is ascertained by the magnitude of the pressure fluctuation" (Barron, 1995). "Therefore, the greater the amplitude of the wave, the harder the molecules strikes the eardrum and the louder the sound that is perceived. However, the range of pressure to which our ears can react exceeds a ratio of one to million and response is not linear" (Blauert, 1983).

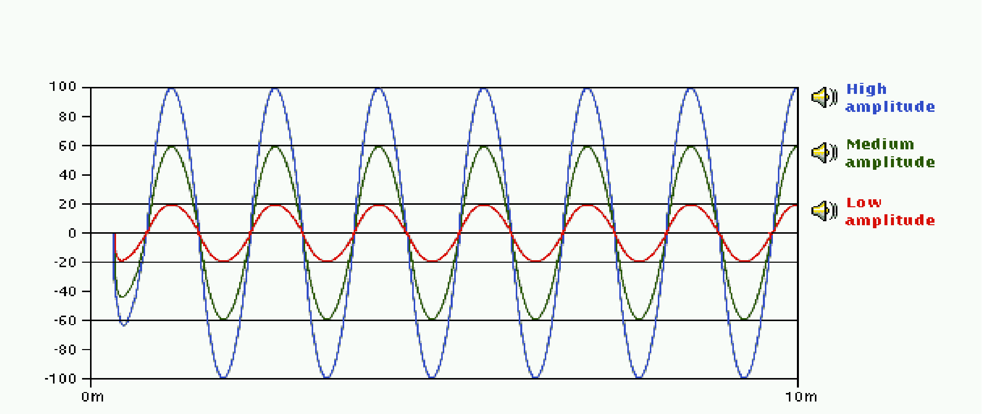


Fig. 2.2: Amplitude illustration (Encarta Encyclopedia, 2008)

5. **Pitch**: **“**This is the subjective response of human hearing mechanism to changing frequency. All musical instruments produce complex sounds which are made up of several frequencies, although the lowest is normally determined by the pitch, the name given to the perceived frequency” (Barron, 2009).

Pitch is the property of sound that we perceive as highness and lowness. A difference in the frequency at which a sound wave vibrates is caused by changes in the pitch, measured in cycles per second (cps). Samples of four notes of different pitch are shown in figure 2.3 with their wave patterns, and as the frequency increases, the pitch also increases, and the note sounds higher. Pitch determines the placement of a note on a musical scale, corresponding to a standard, specified frequency and intensity. It is often used to tune both instruments and voices to one another. Some people have the inborn ability, known as ‘perfect pitch’, to recognize or sing a given note without reference to any other pitch (www.cartaga.org.lb).

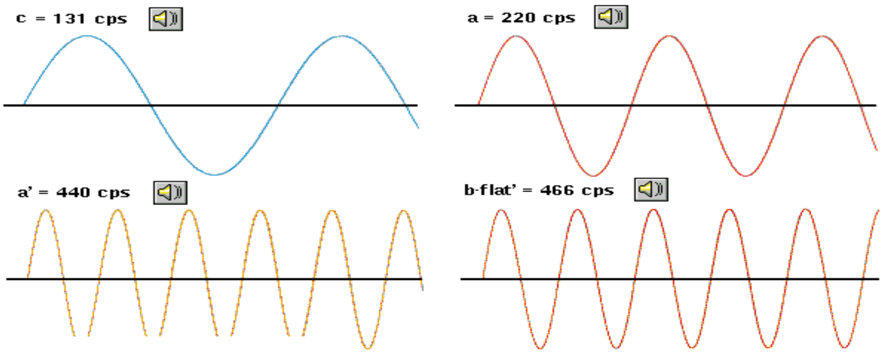


Fig. 2.3: Pitch illustration (Encarta Encyclopedia, 2008)

6. **Sound quality (tone)**: This is the characteristic of sound that allows the ear to differentiate between tones produced by various instruments, even when the sound waves are indistinguishable in amplitude and frequency. Overtones are supplemental components in the wave that vibrate in simple multiples of the base frequency, causing the distinction in quality, or timbre. The ear of humans perceives distinctly different qualities in the same note when it is produced by a tuning fork, a violin, or a piano (CBSE Sample Paper34 Science Class X 2010).

2.2.1 Sound pressure and the decibel

(i) Sound Pressure

Generally, sound pressure is normally measured or calculated in Pascal (Pa) and it is also known as the deviation from ambient air pressure that is caused by sound waves. Figure 2.4 below shows the sound pressure levels and corresponding pressure of various sound sources. It is instigated by the acoustic power output of a sound source, but is modified by the environment between the source and the receiver. “On the other hand, sound power is a characteristic of a sound, while Sound pressure is the effect of a sound as experienced at some specific location” (Walter et al, 2009). Sound pressure must be referenced to a particular point in a space since it usually vary from one place to another in a room .The average smallest sound pressure human ear can detect is around 2×10^{-5} Pascal (Pa). Humans begin to sense sound painful when the sound pressure is around 20Pa (Walter et al, 2009).

Atmospheric pressure has value of 10^5Pa.

Therefore, 1 Pascal = 10^6 micropascal (μPa)

= 1 Newton/metre^2 (N/m^2)

= 10 microbar (μbar)

(ii) The Decibel

The decibel is the unit that is used as measure of a number of acoustical quantities "if the reference value is fixed and known". The decibel stars from 0 for some chosen reference value. It is based on the logarithm of the ratio between two numbers and is equal to 10 bels. "It also describes how much larger or smaller one value is than the other. Some standardized references have been established for decibel scales in different fields of sound. Decibel is strictly ten times the logarithm to the base 10 of the ratio between the powers of two signals" (Rumsey and McCormick, 2009):

Sound pressure level (SPL) in dB = $10\log_{10} ({}^{p}/{}_{p_0})$

Where P = Measured sound pressure of concern [i.e. the sound

Pressure in micro Pascal (μPa)].

P_0= Preference sound pressure usually taken to be $2 \times 10^{-5}\ {}^{N}/{}_{m^2}$

P_0 is the threshold of human hearing of 1000Hz, for measurement in air.

"Decibel is commonly used as the unit for sound pressure level, sound intensity level and sound power level in the field of acoustics" (www.engineeringtoolbox.com).

“It implies that the decibels are not only used to describe the ratio between two signals, or the level of a signal above a reference, but can be used to describe the voltage gain of a device”. “Taking an example of a microphone amplifier which may have a gain of 60dB is the equivalent of multiplying the input voltage by a factor of 1000, as shown below” (Rumsey and McCormick, 2009):

$$20\log\left({}^{100}/_{1}\right) = 60\text{dB}$$

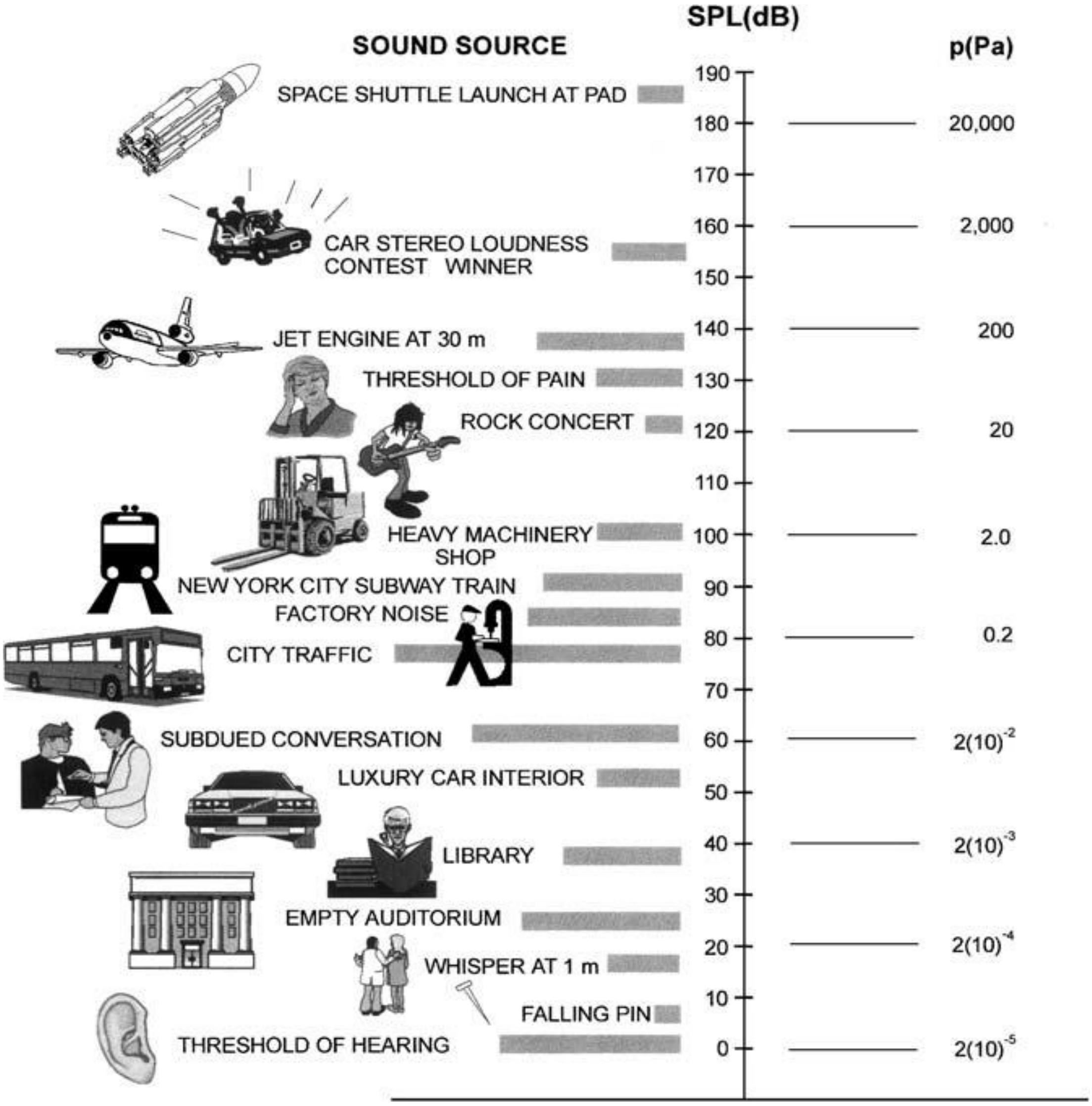


Fig.2.4: Sound pressure levels and pressures of various sounds (Raichel, 2006).

2.2.2 Intensity of a sound

Sound wave always goes along with the flow of sound energy. On this ground, (Salvato, 1982) "describes intensity of a sound wave as the energy transferred per unit time (s) through a unit area normal to the direction of propagation, with a metric unit as $^{w}/_{m^2}$ and measured in decibels (dB)". In practical sense, as in figure 2.5, "the intensity of the threshold of hearing is always 0 dB, while that of whispering is about 10 dB, and rustling leaves reaches virtually 20 dB .The displacements at which a sound can be heard strongly depend on its intensity" (www.scribd.com). For instance, "for a source radiating uniformly in all directions, the sound spreads out in the shape S of a sphere which is equal $4\pi r_0^2$ and the intensity is given by":.

$$I = \frac{W}{S} = \frac{W}{4\pi r_0^2}$$

Where

S = Emitted sound power by the source (W) in watts

r_0 = radius known as the displacement or from the source (m)

I = Intensity of the displacement (W/m^2)

"Therefore, for any point source in a free field, the square of the displacement from the reference point or source varies inversely as the intensity in the radial direction, known as the inverse square law. While in the case of musical instrument the intensity is directly proportional to the amplitude" (Harris, 1994).

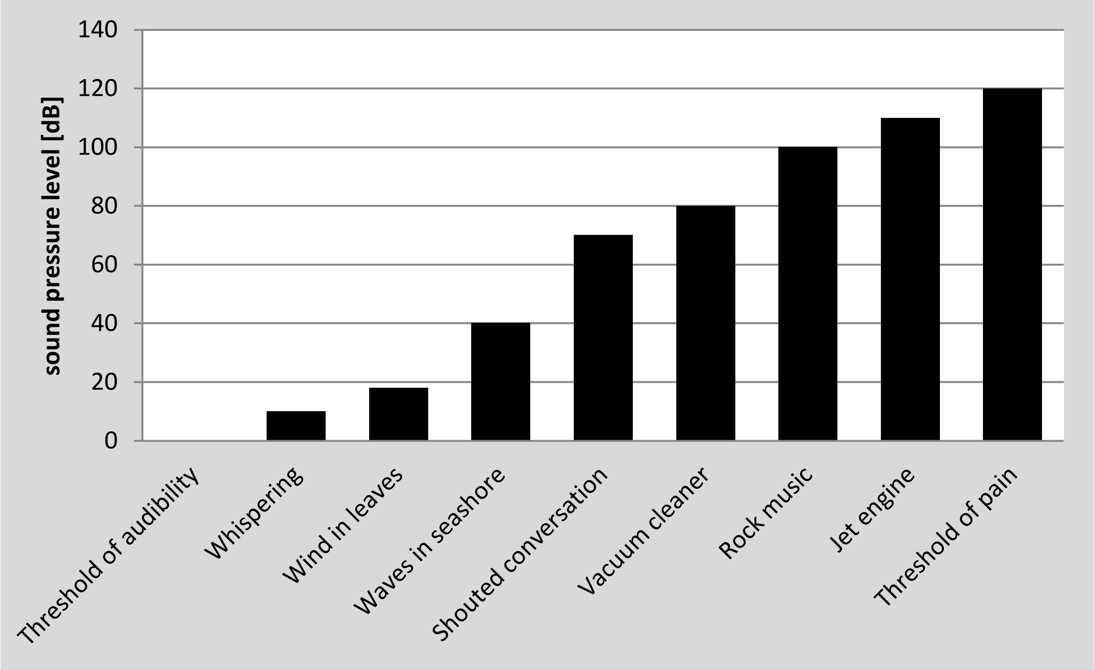


Fig. 2.5: Graphical representation of various sound intensities in decibel (adapted from Raichel, 2006)

2.2.3 Threshold of hearing and threshold of pain

(i) Threshold of hearing

Kinsler et al, (1982) "described threshold of hearing as the weakest sound an average human ear can detect. It is remarkably low and occurs when a distance less than the diameter of a single atom deflects the membrane in the ear". "The value of the threshold varies slightly from person to person but for reference purposes it is defined to have the following values at 1000H_Z" (McMullan, 1983):

When measured as intensity = $1 \text{ x } 10^{-12} \mathrm{W}/m^2$

When measured as pressure = $20 \text{ x } 10^{-6} \mathrm{N}/m^2$

(ii) Threshold of pain

Threshold of pain as described by McMullan, (1983) “is the strongest sound a human ear can tolerate. Very strong sounds become painful to the ear mechanism and very large pressure will have other harmful physical effect, such as those experienced in an explosion, for instance a bomb blast. The threshold of pain has the following approximate values”.

When measured as intensity = $\mathrm{W/m^2}$

When measured as pressure = $200\mathrm{pm}$ or $200\mathrm{N}/w^2$

2.3 Human ear, perception of sound and its consequences

(i) Hearing

Hearing is the perception of sound by human beings or mammals and the sense of hearing includes the ear and the brain (Shepherd, 1994). According to Elert Glenn in Wikipedia, the free encyclopedia of 2004, he stated that “Hearing or audition is the sense of sound perception and results from tiny hair fibers in the inner ear detecting the motion of atmospheric particles within (at best) a range of 20 to 20000 Hz”, as shown in figure 2.6. “He also expressed that Sound can also be detected as vibration by tactition”, although the effect of sound on humans varies from person to person (Wikipedia, 2004).

According to (Encarta, 2008), “humans however, can hear vibrations passing through gases, solids, and liquids. In some cases, sound waves are transmitted to the inner ear by a method of hearing called bone conductivity”. “People can hear their own voice partly by bone conductivity” (Encarta, 2008). Table 2.4 shows the comparison of frequency ranges for some common sounds and human hearing.

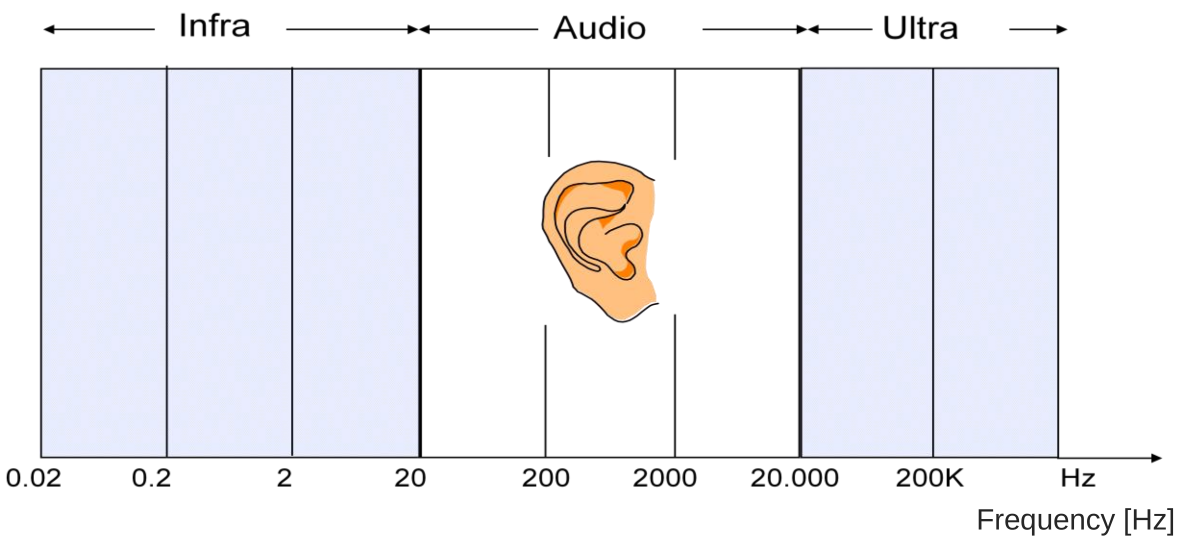
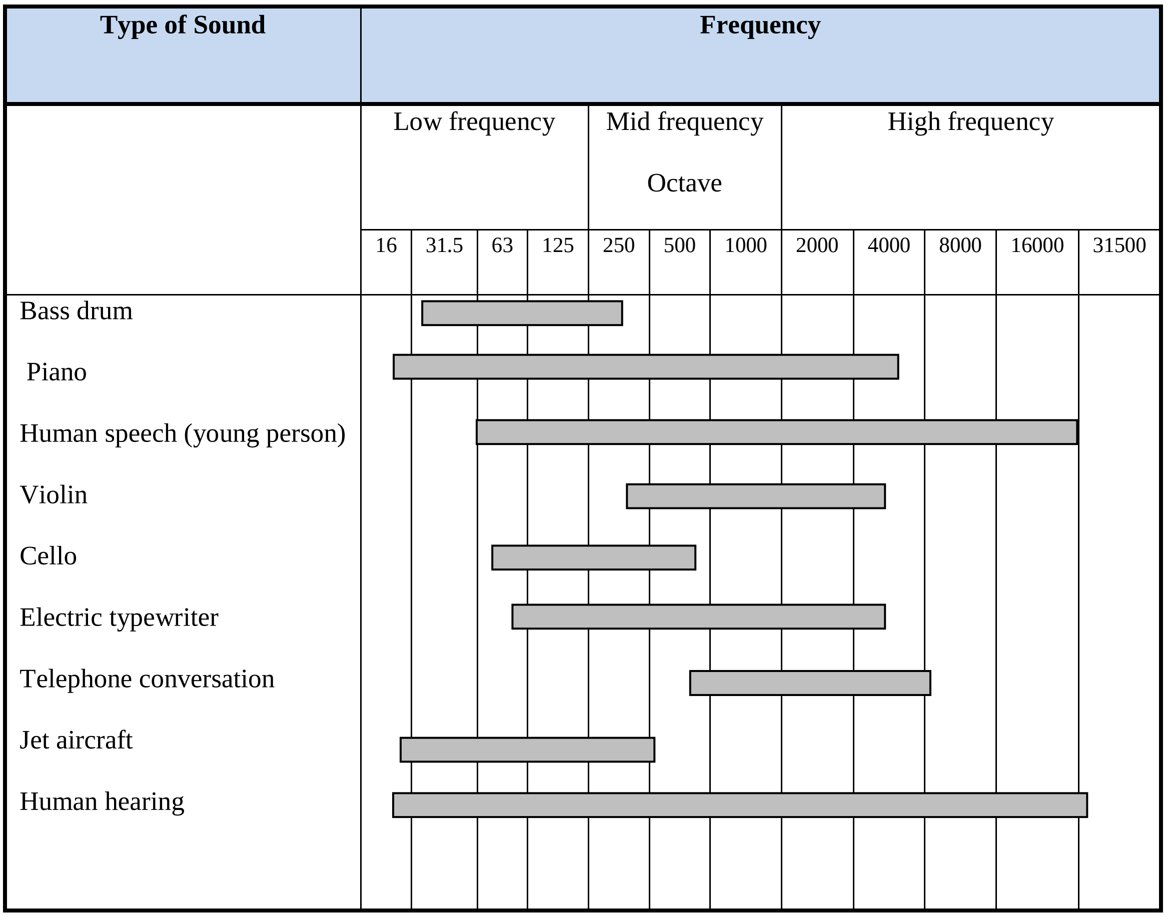


Fig.2.6: Human range of hearing

Table. 2.4: Frequency ranges for common sounds



Sources: (Adapted from Walter, T and el at, 2009: Cavanaugh and el at, 2010)

Health and medical online article, (2011) “reports that the voice causes the bones of the skull to vibrate, and these vibrations directly stimulate the sound-sensitive cells of the inner ear”. “Only a comparatively small part of a normal person’s hearing depends on bone conductivity, but some totally deaf people can be helped if sound vibrations are transferred to the skull bones by a hearing aid” (auuuu.org, 2011).

(ii) Human Ear

Research has shown that in vertebrate, the organ of hearing and balancing is the ear and practically only animals with spinal column or cord, have ears. Similarly, Invertebrate animals, such as jellyfish and insects, lack ears, but have other structures or organs that serve similar functions (Camhi, 1984). According to Culliney John’s article in Microsoft Encarta online encyclopedia, (2000) he explains “that among other animals the most complex and highly developed ears are those of mammals”. Furthermore, he also states that whale has a highly develop brain and are among the most behaviorally complex of all animals.

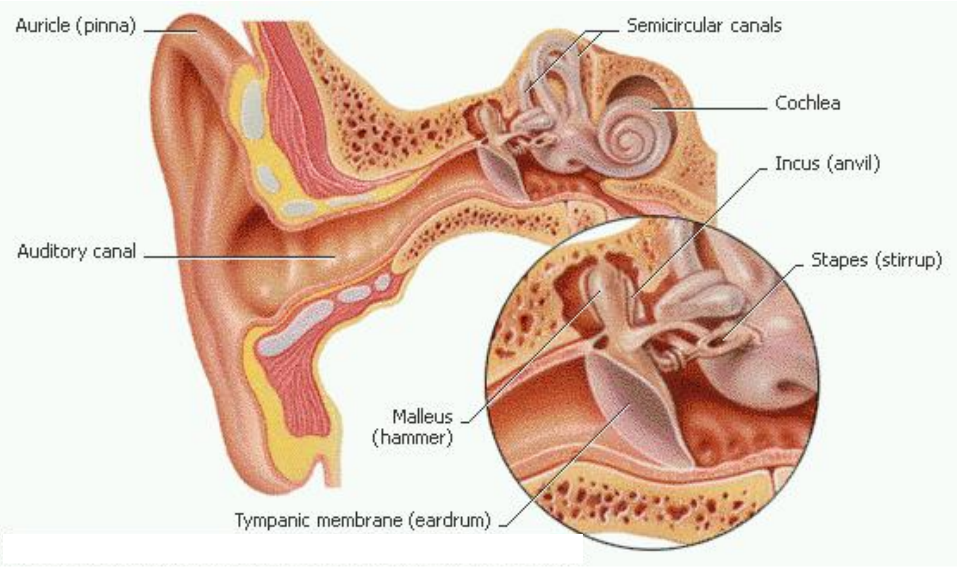


Fig. 2.7: The Human Ear (Encarta Encyclopedia, 2008)

“The Structure of the human ear is segmented into three major parts; the outer or external ear, middle ear and the Inner ear” (Ervin, 2010). Fig 2.7 gives an illustration of the external ear of a human. Ervin also confirms in her article of 2010 that the outer or external ears are made up of three structures; the external auditory meatus and the cartilaginous auricle or pinna. She further explains “that the pinna or auricle collects and directs sound waves traveling in air into the ear canal or external auditory meatus”. The external ear in humans is not well developed as in animals, for example animals like dogs and cats. The pinna, “(i.e. the visible part of the ear that is attached to the side of the head, and the waxy, dirt-trapping auditory canal) in human detect the direction of sound by channeling collected sound waves into the external auditory meatus” (Bhatnagar, 2002).

According to the health and medical online article of 2011, “the tympanic membrane (eardrum) separates the external ear from the middle ear, an air-filled cavity between the tympanic membrane and the cochlea of the inner ear” (auuuu.org, 2011). “Bridging this cavity are three small bones-the malleus (hammer), the incus (anvil), and the stapes (stirrup)” (Turner and Pretlove, 1991).

Bhatnagar, (2002) confirms “that the human inner ear comprises of two distinct sensitive parts the cochlea and semicircular canals”. This canal on the other hand serves as the resonator, allowing peak resonance for the frequencies that are important for most human voice. The semicircular canals are also concerned with balance (Bhatnagar, 2002).

“The outer and middle ears function only for hearing, while the inner ear also serves the functions of balance and orientation” (Blauert, 1983).

Report has also shown “that some animals can only detect vibrations passing through the ground, while some can hear sound or vibrations passing through water” (auuuu.org, 2011). “The ear of humans is capable of hearing many of the sounds produced in nature, but certainly not all sounds can be heard by them” (Blauert, 1983).

However, “low frequencies like a heartbeat of 1 or 2 Hz cannot be heard by humans, unlike sonar sounds produced by dolphins which are too high”. “Frequency that is below the human range is known as infrasound, but may be detected by a creature with big ears, such as Elephant” (Broner, 2008).

Recently, research indicates “that elephants can also communicate with sound that is lower in frequency than 20 Hz (Hertz) or cycles per second, the normal limit of human hearing known as infrasound”. For example, “animals like Bats which can detect sound with frequencies as high as 100,000 Hz, whales, porpoises, and dolphins use ultrasound for their navigation; sound that is above the range of the human ear” (Broner, 2008). Fig 2.8 shows the frequency ranges for various animals.

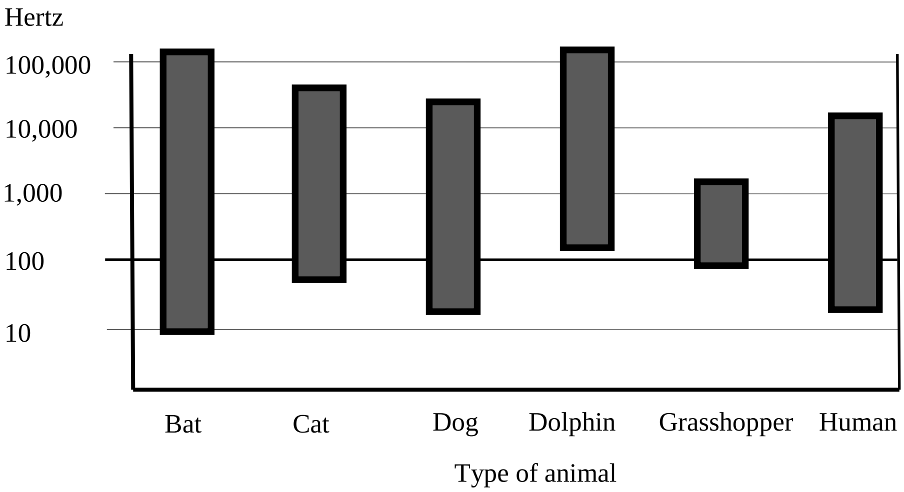


Fig. 2.8: Selected mammals hearing frequencies (adapted from Raichel, 2006)

2.3.1 Consequences of noise on humans

According to (Kinsler et al, 1982), he described that the effect of noise on human emotions ranges from annoyance, anger, and to psychological disruption.

He asserts that physiologically, noise can varies from harmless to painful and physically damaging. Furthermore, he avers that noise can affect economic factors by decreasing workers efficiency, affecting turnover and altering profit margins.

According to the publication of World Health Organisations (WHO) of 1998 on Environmental Health Criteria, (Berglund and Lindvall, 1995) defined health as "a state of complete physical, mental and society well-being and not nearly the abuse of disease infinity". Their statement shows that excessive noise is clearly a health problem to humans.

Cheremisinoff, (1996) on the other hand categorized the effects of noise as; "annoyance, effect on human performance, induced hearing loss effect, nonauditory health effects, individual behavior effects, effects on sleep, communication interference effect, effects on domestic animals and wildlife".

Apart from the effect of noise listed above, it also affects the "circulatory and nervous system". "The effects of noise are difficult to assess at a time, since individuals react differently to noise depending on age, sex and socioeconomic background". "The relationship of noise to productivity or performance is contradicting and not well established, but over a longtime it may be a terrible health hazard to the body system". "Some booms like bomb blast or gunshot can cause physical damage to the entire body structures over a time period, which indicated that long time exposure to high level noise is more harmful than intermittent noise on occasional exposure” (Jacko and LaBreche, 2009).

“High and middle frequency sound at high levels is generally more harmful than low-frequency sound at the same level”. Therefore, “greater harm is done with increased time of exposure” (Murray and Lewis, 1995).

2.3.2 Acoustic trauma

Martin and Martin (2010), states that “acoustic trauma is an injury obtain in the hearing mechanisms, which usually occurs in the inner ear due to very loud noise (noise level greater than 140-150 dB), such as an explosion near the ear, gunshot or long-term exposure to loud noises (loud music or machinery)”. “It is a common cause of sensory hearing loss which may lead to the damage of the ear drum, ossicles, and the hair cells, supporting cells and tissues of the organ corti” (Salvi et al. 1998).

2.3.3 Temporary threshold shift (TTS)

William (1991) ,“defined temporary threshold shift as a temporary change in hearing level that recovers between exposures, resulting from sound levels over about 70 to 75dB (A)”. For instance, “If a car radio is turn up after a noisy work day, then it may found out that the next morning there will be an increment in the sound of the radio, in this case we may be experiencing TTS and this may last, depending on the nature of the exposure and the individuals, for minutes, hours, or days, after the sound has stopped”. “As long as intervals between exposures are long enough for complete recovery, it is unlikely that permanent damage will occur”. “It is thought that TTS is due to reversible biochemical changes to the stereocilia of the hair cells” (Melnick, 1991).

2.3.4 Permanent threshold shift (PTS)

“This is as a result of continued or repeated exposure to excessive noise over a period of time, which may lead to permanent damage to the ear, although this process occurs gradually”. “Normally, it is the hair cells in the inner ear, which detect the 4-6 kHz frequencies, which deteriorate first” (William 1991). “As most of the speech frequencies are below this range, the loss may initially go unnoticed”. “With further excessive noise exposure, the hearing loss increases and extends down to lower frequencies as well and the person begins to have trouble understanding speech” (Gelfrand, 2009).

2.3.5 Tinnitus

“Tinnitus is the term given to noises which are perceived in the ears or in the head; such noises can be running, buzzing, hissing, whistling, and pulsing”. “It can also be other sounds which do not come from an external source” (Gunn, 2009). “Research into the causes of tinnitus is still ongoing”. “However, the current theory is that damage to the hair cells of the inner ear causes the generation of weakness, abnormal nerve impulses, which are mistakenly perceived by the brain as real external sounds” (Gunn, 2009: Gelfrand, 2009).

2.4 Source of unwanted noise

The source of noise must be determined by professionals if lasting solutions are to be provided to noise pollution in our society. Different people have identified a number of sources of noise pollution in our environment.

According to (Salvato, 1982), he classified the major sources of noise pollution as; urban noise, commercial activities noise, residential contribution noise, and community noise.

On the other hand, sources of noise are classified by Templeton (1997), “as transportation/road traffic noise, aircraft noise, railway noise, aircraft noise, construction noise, industrial noise, and leisure/entertainment noise”.

2.5 The behavior of sound in an enclosed space

Propagation depends on the source of sound and a receiver, but the propagation medium is all around us (Barron, 1993). Thus, (Harris 1994) “defined sound as an oscillation of the atmosphere which is capable of being detected by the human ear” and thereafter (Mehta et al, 1998) averted that “Listeners perceive sound because pressure fluctuations vibrate the ear drum and cause electronic impulses to be sent to the brain, which are in turn interpreted as sound”. Barron (2003) also argued that “sound is actually a process that consists of three components such as the sound source, the sound path, the sound receiver and all the three components must be present for sound to exist”. According to JISC Digital Media of 2009, “sound can be altered by its immediate environment and any further physical mediums it passes through after initial excitation”.

An enclosed space is a room or area bounded on every of its sides. As shown in figure 2.9, “when a sound wave strikes a material such as a partition or wall, some portion of the energy will be absorbed, a portion will transmit through the material to the other side, and the final portion will be reflected back into the space”.

“As a result, the sound at any point in the room is a combination of direct sound from the source plus reflected sound from walls and other obstructions” (Beranek, 2004). If reflections are so large that the sound level becomes uniform throughout the room, then at that particular point the acoustic field within the room is said to be diffused (Walter et al, 2009).

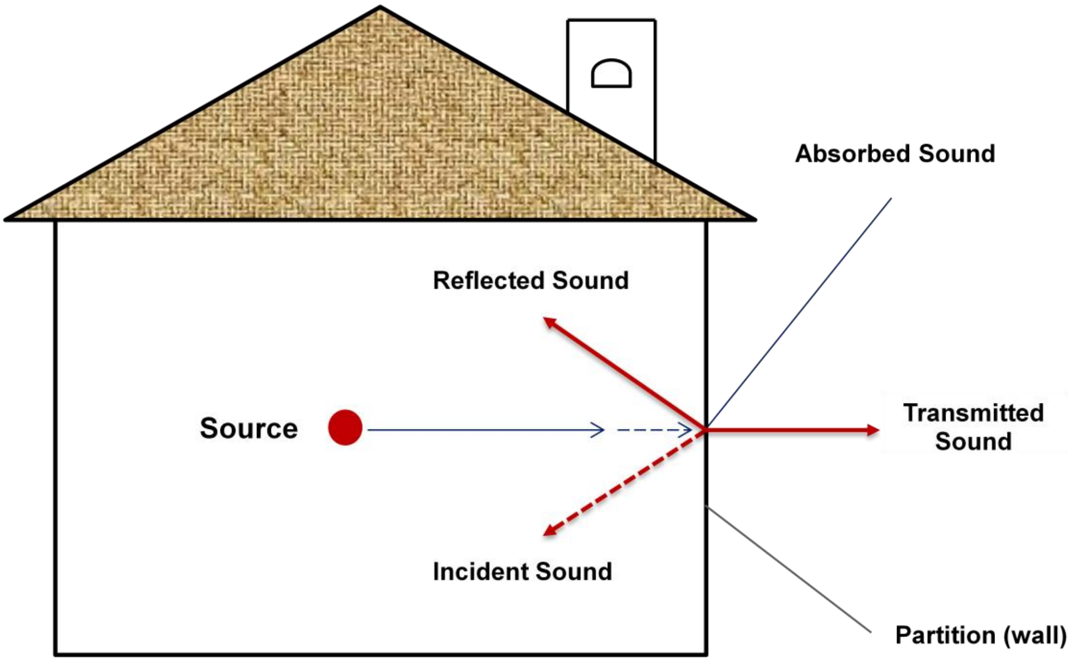


Fig. 2.9: Reaction of Sound Striking a Partition wall (Researcher's field study, 2011)

The effect of indirect sound may be pronounced in spaces enclosed with materials that do not allow the passage of sound rays through them. Adjustments to the material to aid diffusion will improve the acoustic of the space. Some of these materials can absorb sound, reducing the effect of indirect sound. Heavy dense materials, such as concrete, plywood, gypsum board, or steel, are excellent attenuators. They are nonporous and good reflectors of sound energy (Pelton, 1993). In certain situations, reflecting surfaces are needed to direct sound waves in a desired direction that will, in turn, absorb or diffuse the sound waves (D'Antonio, 2008).

In a practical sense , when a sound wave strikes a barriers posed by an enclosure, sound waves are likely to behave in the following ways:

(i) Sound Transmission

(ii) Sound Reflection

(iii) Sound Absorption

(iv) Sound Diffusion

(v) Sound Diffraction

(vi) Direct and indirect sound

2.5.1 Sound transmittance

Hammershoi and Moller (1996), “defined sound transmittance is the ratio of transmitted sound to the incoming sound. They also confirms that the ratio of sound intensity on the receiver side to the sound intensity on the source side of the partition element”. “Efficiency of walls and floors in preventing sound transmission depends on their mass, the heavier the construction the less easily it is set into vibration and the higher its vibration values” (Diament, 1986) . For instance, a sound travelling from a room to an adjacent room (i.e. the receiving room), as shown in figure 2.10. The transmitted sound level to the receiving room will depend on three basic factors which are as below;

> *“The sound – isolating properties of the wall (i.e. sound transmission loss), the total surface area of the common wall that radiates sound into the adjacent room, and the total sound absorption present in the receiving room”* (Cavanaugh and Wilkes, 1999).

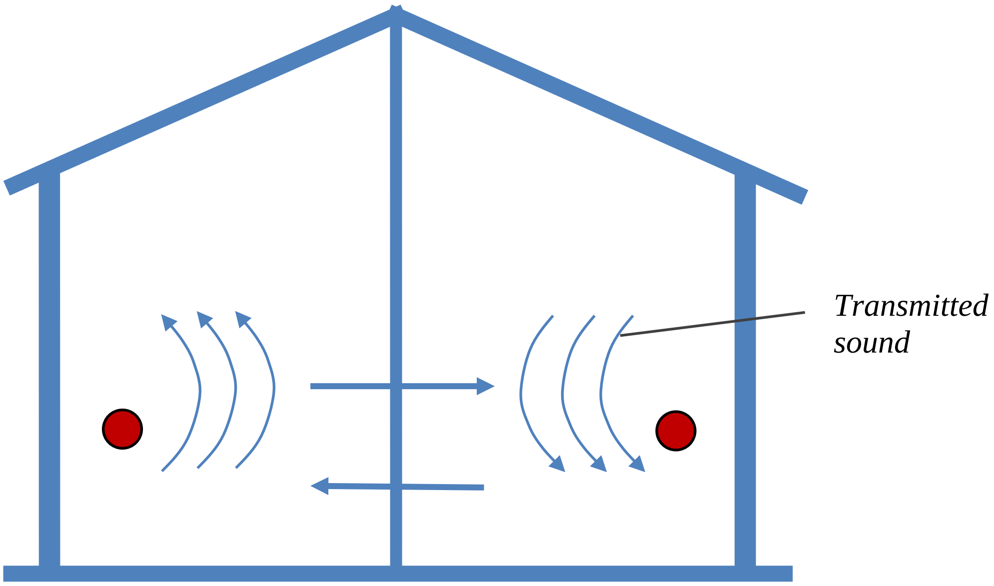


Fig. 2.10: Sound transmission into adjacent room.

2.5.2 Sound reflectance

According to D’Antonio (2008), Sound reflectance is the ratio of the reflected sound to the incoming sound. In certain situations, reflecting surfaces are needed to direct sound waves in a desired direction that will, in turn, absorb or diffuse the sound waves (D’Antonio, 2008). The first thing a listener hears in an enclosed room is the direct sound, which then travels in a straight line from the source and subsequently accompanied with series of early reflections from side walls, ceiling, floor etc. Sound that cannot be absorbed continues to be reflected in the room and as a result perceived as an echo by the listener, as illustrated in figure 2.11. However, most reflection in an enclosed space is not heard as echoes. Thus, for a reflection to be heard as an echo it must arrive at least 50ms later than the direct sound. To perceived sound as an echo requires reflection from a large surface by a path simpler than other reflections of the same delay, or reflection involving focusing (Barron, 2009).

The matter of predicting reflection whether reflections will be audible as echo is not trivial (Cremer and Muller, 1982). At first one might not hear as an echo, but once it is detected one may be unable to ignore it (Blauert, 1983).

Fig. 2.11: Reflection Illustration (Adapted from Harris, 1994)

2.5.3 Sound absorption

When sound waves hit the surface of an obstacle or a wall, as shown in figure 2.12, “some of its energy is reflected while some are lost through its transfer to the molecules of the barrier. The lost sound energy is said to have been absorbed by the barrier” (Walter et al, 2009). “The thickness and nature of the material as regards its softness and hardness influences the amount of sound energy absorbed” (Alton, 2001).

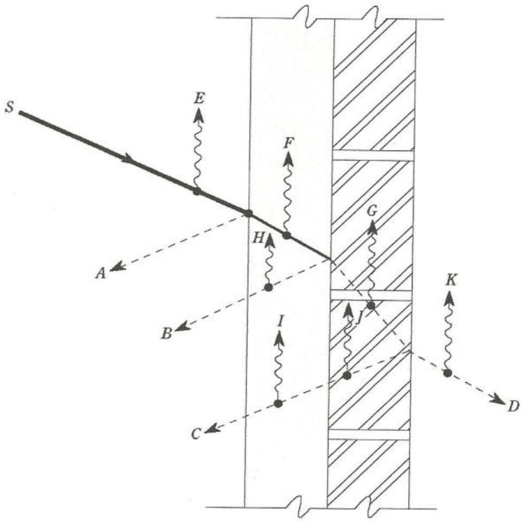
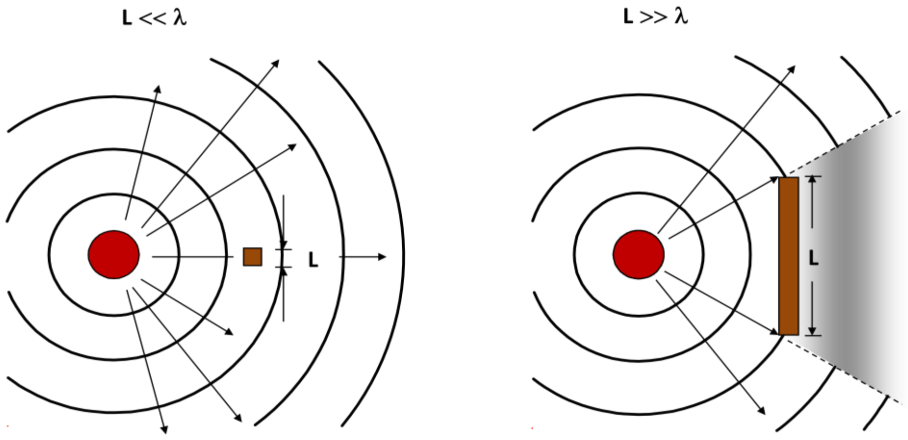


Fig. 2.12: Absorption on a wall with acoustic material (Alton, 2001)

2.5.4 Diffraction of sound

When a sound wave hits an obstacle, as illustrated in figure 2.13, they spread around the edges of the obstacle to give rise to diffraction of sound. In other words, sound waves are bent or their directions of propagation are changed due to the obstacle placed in their paths. Also, sound waves are diffracted rather than reflected if their wavelengths are comparable with the dimensions of the reflected objects (William, 1971).



(a) (b)

Fig. 2.13: Diffraction of sound [(Brüel and Kjaer, 1998) -Sound and vibration measurement A/S]

From figure 2.13, in (a) If the obstruction L << the wavelength, then the obstruction is negligible, while in (b) If the obstruction L >> the wavelength, then the effect is noticeable as shadowing effect.

2.5.5 Scattering of sound (diffusion of sound)

This is the scattering of waves from a surface, as portrayed in figure 2.14. It occurs when a noise source emits sound continuously in a room; the room is field with reflected sound waves travelling in many different directions. Harris (2004) asserted that “greater the uniformity of the reflected sound levels in the room, the greater the diffusion in the room”. “Sound is said to be absolutely diffuse in a room if the degree of the reflected sound is everywhere equal and if the reflected sound waves travel in all directions with equal probability, although it is difficult to determine the direction from which the sound originates unless one is close to the source” (Harris, 1994).

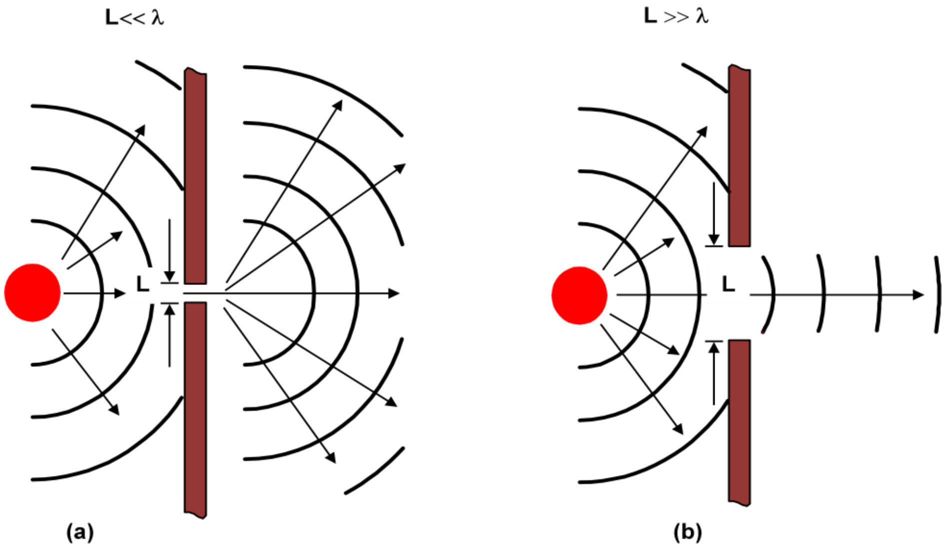


Fig. 2.14: Diffused sound [adapted from (Brüel and Kjaer, 1998) -Sound and vibration measurement A/S]

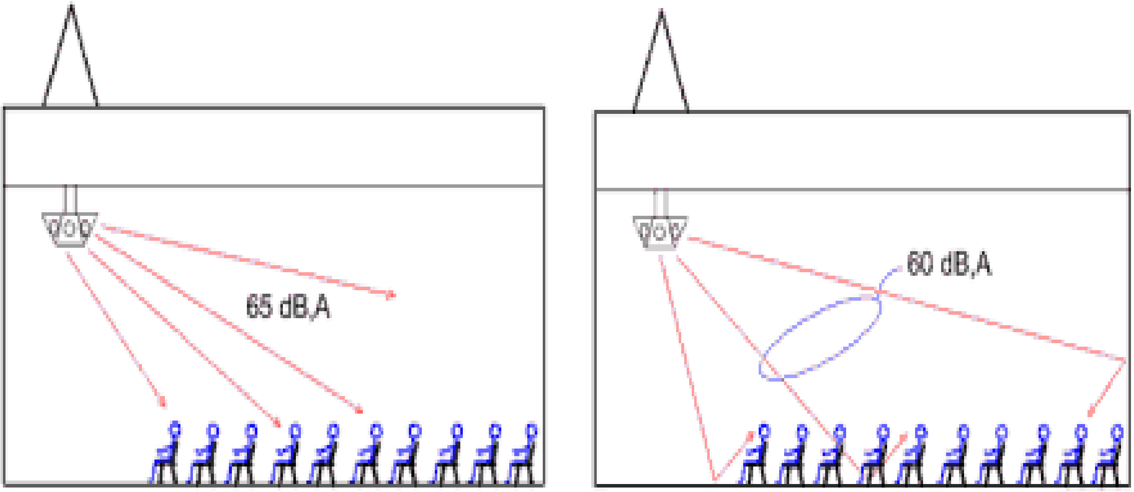
From figure 2.14, in (a) If the obstruction L << the wavelengths, then sound re-radiate in an omnidirectional pattern, while in (b) If the obstruction L >> the wavelength, the sound passes through negligible disturbance.

The principal means of providing diffusion of sound in a room according (Harris, 1994) are as follows

1. Irregularities of the wall surfaces, for example, large splays, convex surfaces, pilasters, coffers, and surface ornamentation.
2. Objects within the room that scatter the sound, for example, free standing columns, statues, or chair.
3. Sound- absorptive materials that are nonuniformly distributed in the room (this contribution to the diffusion of sound in a room is usually much less significant than the above two contributions).

2.5.6 Direct and indirect sound

As shown in figure 2.15, in (a) direct sound leaves the speaker and have receives impact on listeners' whereas in (b) indirect sound bounce off from nearby surfaces to the audience. "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" (Raichel, 2006). But indirect sound that a listener hears comes from a great number of reflection paths. Direct sound is always vita when it comes to speech intelligibility. It is so because it does not affect anything in the room, and thus is clear and distinct (Armstrong, 2003).



(a) Direct signals leave the Speakers and impact the audience

(b) Indirect signals bounce off nearby surfaces to Audience

Fig: 2.15. Reception of direct and indirect sound (Arthur, 2002).

On the other hand, reflected sound takes longer period to reach the listener compared to direct sound, because its path to the listener is longer. Reflected sound can be good or bad depending on the time delay (Armstrong, 2003). “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” (Raichel, 2006).

“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” (Raichel, 2006).

“For a source operating in a reverberation chamber the gain intensity can be considerable-as much as ten times the initial level and approximately proportional to reverberation time. Thus, it can be desirable to have a long reverberation time to render a weak sound more audible” (Bistafa and Bradley, 2000).

2.6 Reverberation

In a practical sense, “when a sound source stops emitting energy in an enclosed space or hall, it takes some time for the sound to become imperceptible to the ear. This prolongation of the sound in the room caused by continued multiple reflections are called reverberation” (Cavanaugh and Wilkes, 1999); as illustrated in figure 2.16.

In large halls, the number of reflections arriving at times later than one-tenth of a second after the direct sound (= 100 ms) [i.e. 34m (0.1s)] is so high that individual reflections are no longer distinguishable. The late sound after 100ms is called reverberant sound. Reverberation is particularly obvious in a large church or cathedral spaces (Barron, 2009).

“Despite that reverberation is due to continued multiple reflections, controlling the reverberation time in a space does not ensure that the space will be free from reflection and other acoustic defects or problems, since high reverberation time will cause a build-up of the noise level in a space” (Bistafa and Bradley, 2000).

Bradley et al (1987), avers “that reverberation time **(RT60),** and background noise level measurement have traditionally been used to describe auditoria acoustical issues or problems”.

Fig. 2.16: Reverberation Illustration (adapted from Harris, 1994)

Haas (1972) depicts direct sound as the pleasurable effect of sound reflection that arrives at the listener's ear within short time, thereby increasing the apparent loudness of the sound.

"Reverberation time **(RT_{60})**, has effect on both musical conditions and understanding of speech. It is always an issue in a given space or hall, thereby making it difficult to select an optimum reverberation time in a multi-function space, as different uses require different reverberation times" (Kang, 2002). "A reverberation time that is optimum for a music program might not be conducive to that of speech and could be disastrous to the intelligibility of a spoken word" (Barron, 1993). The desired reverberation time for a room depends on the volume of the space and the type of room use, as shown in the table 2.5, optimum reverberation for auditoriums and similar facilities.

2.6.1 Echoes and Flutter echoes

Echoes are known to occur whenever an isolated reflected wave arrives at the ear of a listener more than 67 ms [i.e. 0.067sec (22.78m)] after the time of arrival of the original sound. In auditoriums, there are many reflected waves that arrive at the ear at time intervals greater than 70 msec [i.e. 0.07sec (23.8m)] because the reverberation time may be as high as several seconds (Beranek, 1986).

Flutter echo reiterated many times, which involve short path lengths and occurs between two parallel walls. The repeated reflections create a acteristic ‘twang,’ which is obvious to anyone who heard it by clapping their hands in the corridors or rooms with flat parallel walls, as shown in figure 2.17. In auditoria, musician should not be between two parallel surfaces. Flutter echoes are heard when just few musicians are present. Reorientation of one of the parallel surfaces by only 5° is adequate to cure it (Bradley, 1992).

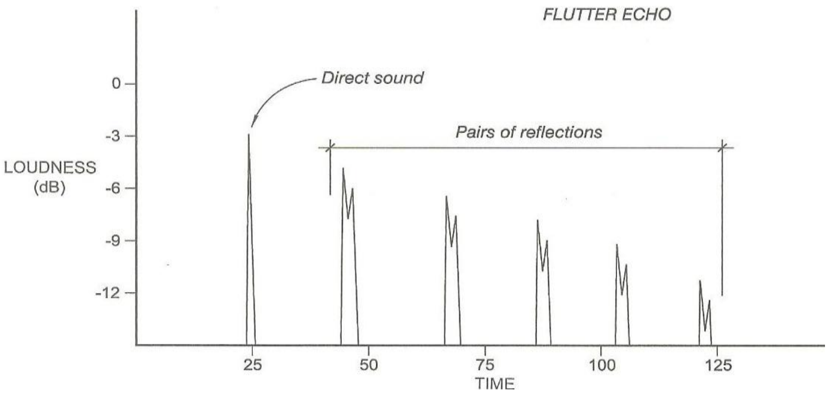
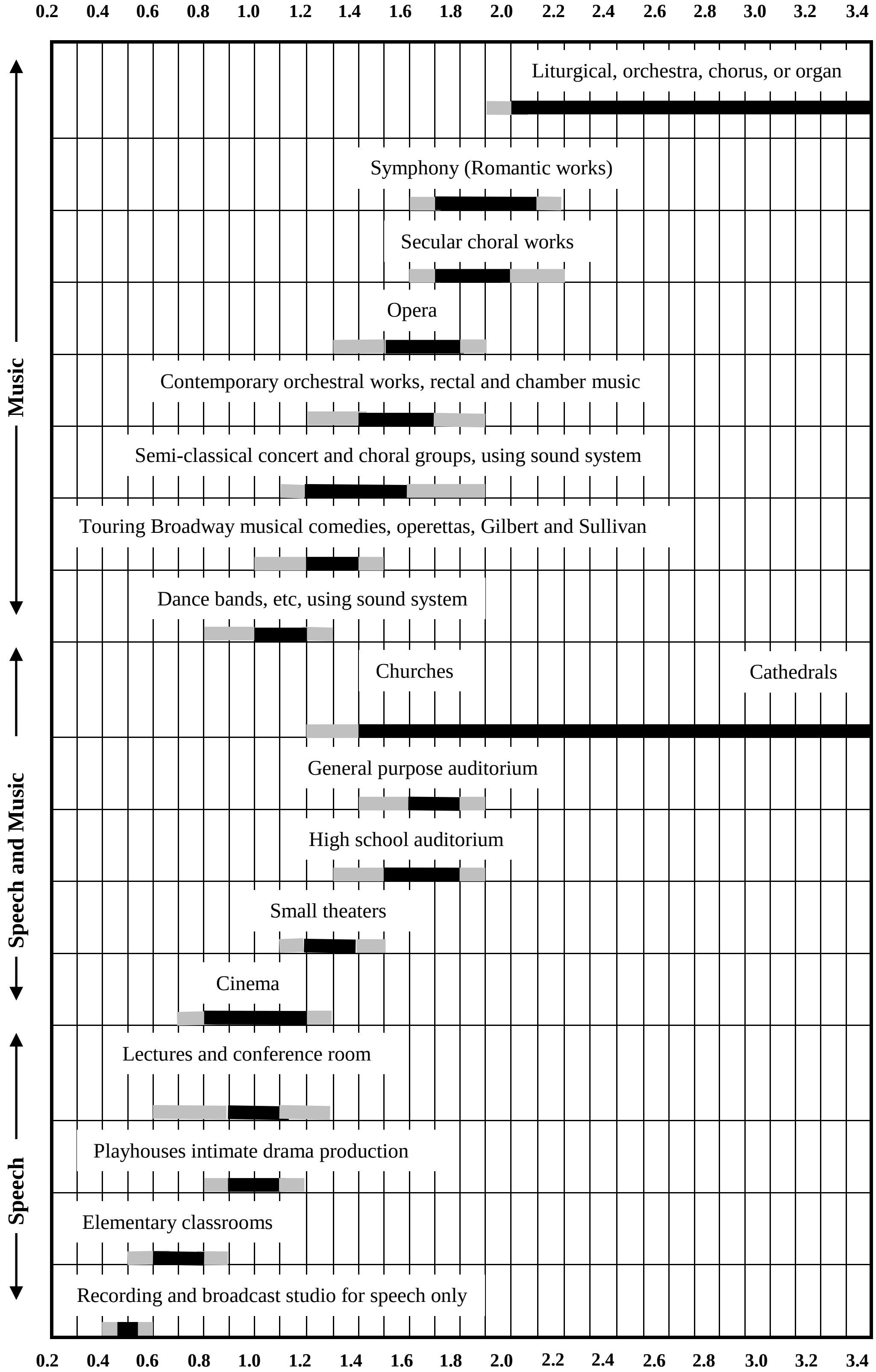


Fig. 2.17: Impulse response showing flutter echo between two parallel wall surfaces (Cavanaugh and Wilkes, 1999)

Table.2.5: Optimum reverberation (500-1000 Hz) for auditoriums and similar facilities.



Source: (Adapted from Johnson, R. et al, 1990: Cavanaugh and Wilkes, 1999)

2.6.2 Airborne and structure-borne sound transmission

Airborne and structureborne sound transmission are the process in which sound are transmitted into buildings either through air and bounce into the adjoining spaces or within the structure itself but perceived as airborne sound after its transmission.

2.6.2.1 Airborne sound

According to Means (2009), "airborne sound transmissions are sound traveling through the air and subsequently through partitions and openings, such as through the walls, windows, floors and doors", as illustrated in figure 2.18. Sound transmission through the wall, doors, windows, ceiling, and floor has no direct connection with absorption. However, "transmission occurs as a result of constructional member being set into vibration by incident sound and giving rise to vibration in the air at far side, thereby generating sound into the adjoining space" (Kinsler et al, 1982).

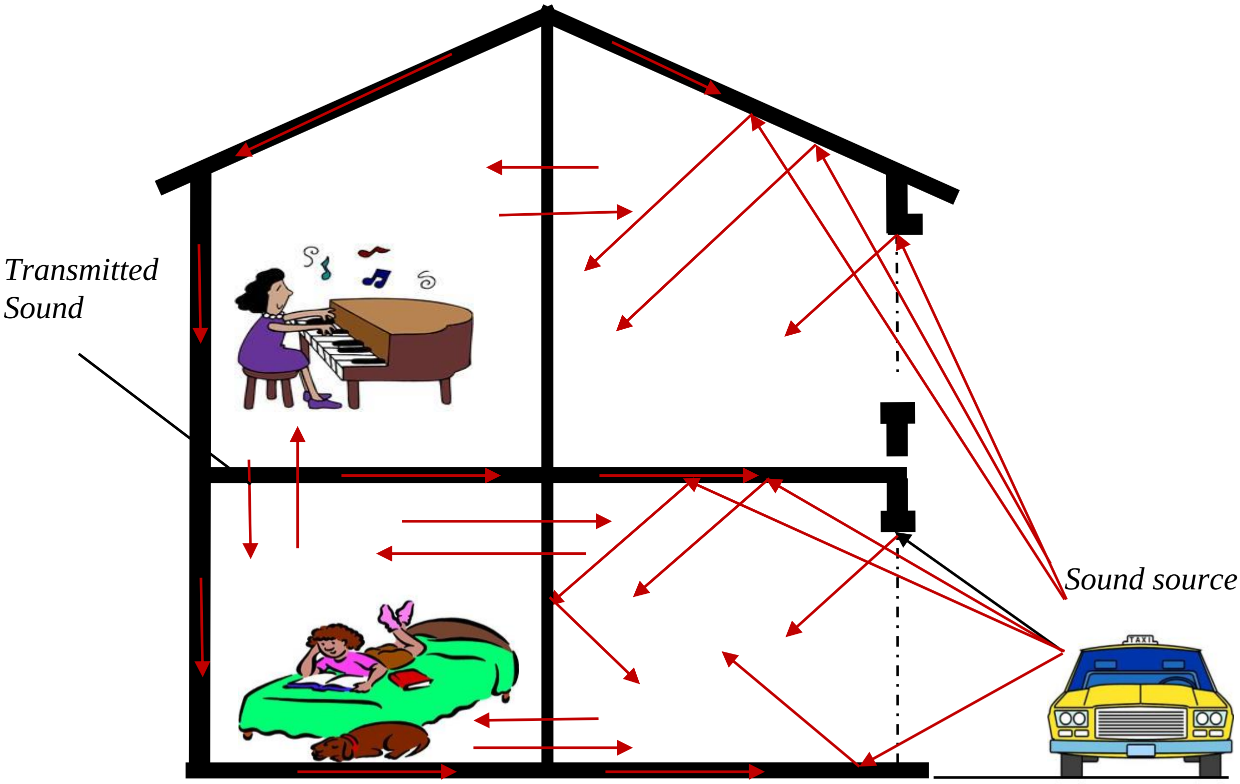


Fig. 2.18: Airborne sound illustration (Adapted from Harris, 1994)

“In a case where partitions has holes or cracks (leaks) through it, or if it is porous, the sound waves can also be transmitted to the adjacent side of the partition by these leaks or pores” (Harris, 1994). Considering the sound insulation for the partitions and sound leaks is also of importance in this case.

a) **Sound transmission loss (TL):** This is known as the measure of the airborne sound insulation it provides and is calculated in dB. The transmission loss (TL) of a partition that is acoustically transparent is zero (0) dB, which implies that the heavier or more complex a partition is, the higher its sound transmission loss (i.e. a partition or construction that transmits little amounts of the incident sound energy will have a high sound transmission loss). Since the frequencies of sound transmission loss differ, as it is increasing the frequency increases also, as portrayed in figure 2.19 and 2.20, for three different partitions (Harris 1994: Cavanaugh and Wilkes, 1999).

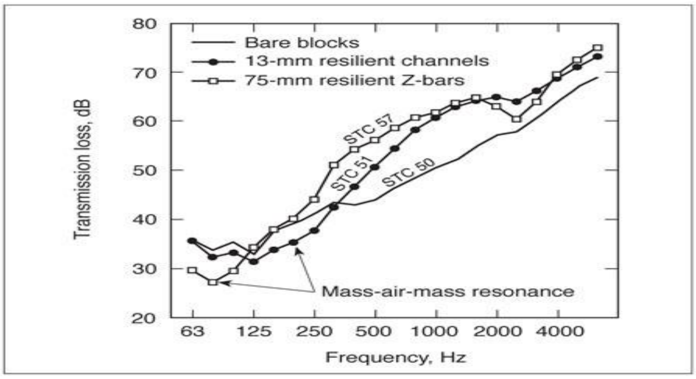


Fig. 2.19: “Sound transmission loss (STL) through a 190-mm concrete block wall with 15.9-mm gypsum board attached to one side using a) 13-mm resilient metal channels, and b) 75-mm resilient Z-bars” (Warnock, 1998).

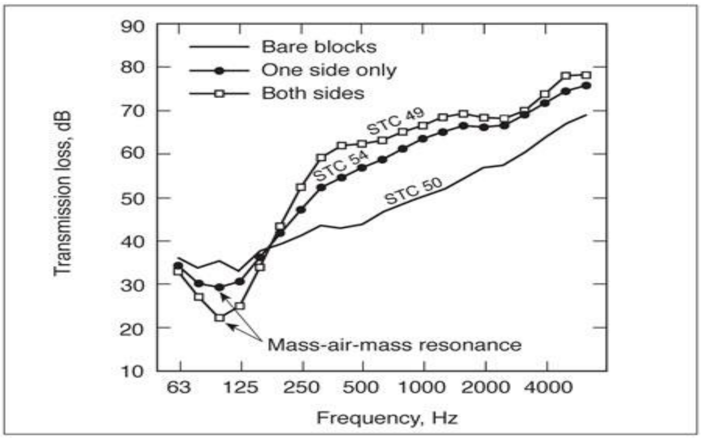


Fig.2.20: “Sound transmission loss (STL) for a 190-mm concrete block wall with glass fibre batts in the cavity and with 15.9-mm gypsum board attached on 13-mm resilient metal channels to (a) one side and (b) both sides of the wall” (Warnock, 1998).

b) **Sound transmission class (STC)**: This is known as a general technique of classification of partitions by transmission loss performance; “a good single-number descriptor is usually desirable to indicate the sound isolating capacity of the partition, such as speech, radio, and TV” (Warnock, 1988). Though, sound insulation differ with frequency and not same for different type of partition. It is convenient to compare the effectiveness of two partitions using a method of rating sound insulation that can be represented by a single number (Huntington and Mickadeit, 1981).

The single-numbered rating of sound insulation known as sound transmission class is most prevalently used in North America. When a partition allow for no airborne sound insulation, then it is said that the STC rating is zero (0) and the higher the STC rating, better is the sound insulation provided by a partition. Figure 2.21; illustrate the STC rating for various types of wall constructions.

However, in other countries than North America, weighted sound reduction index (R_w) used instead of sound transmission class to express the overall sound insulation since it is somehow similar to sound transmission class. The procedures for rating sound transmission class are standardized in ASTM E 413 (Harris, 1994).

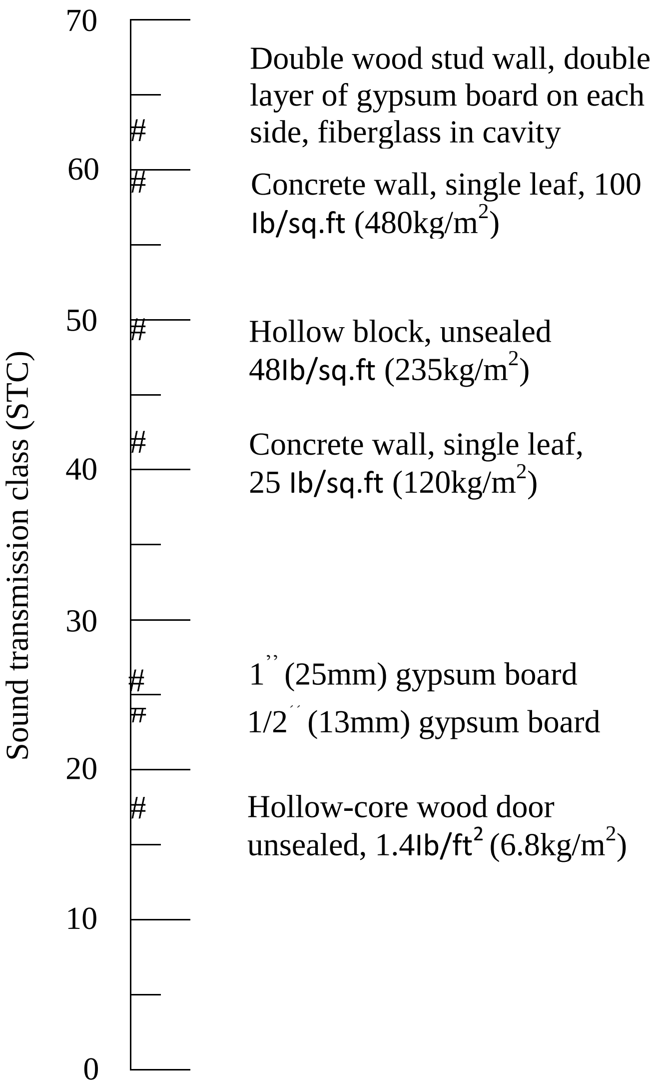


Fig.2.21: Sound transmission class (STC) ratings of a number of common wall constructions (Source: Harris, 1994)

c) **Sound leaks**: This is the process in which sound passes through crack or hole in a building, such as through partition and can reduce the effectiveness of the sound insulation which it provides. The use of lightweight demountable partition system might cause severe sound leakage at the panel joint, floor, ceiling tracks and side wall intersections, which is even more damaging. Materials and system to be used must be detailed and specified to issue positive panel joint seals that will perform effectively over the expected life of the partition installation (Huntington and Mickadeit, 1981). Figure 2.22; illustrate some sound leakage and flanking transmission paths between a structure rooms.

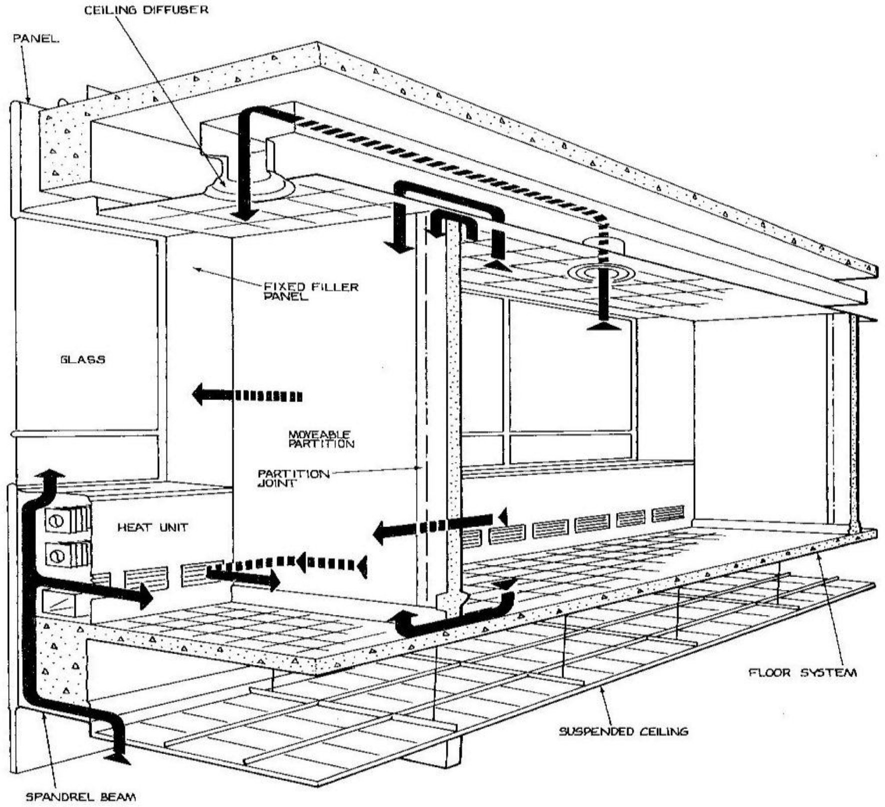


Fig.2.22: Sound leakage and flanking transmission path between rooms (source: Cavanaugh and Wilkes, 1999).

2.6.2.2 Structureborne sound

Möser, (2009), simply "defined structure-borne sound as sound energy transmitted through solid elements or structure of a building". When sound energy is directed induced into a structure (by the impacts of footsteps, dropping of an objects on the floor, hammering, or by rigidly attached vibrating mechanical equipment, slamming of the door, etc), the energy will travel relatively easily throughout the structure and reradiate as air born sound in adjacent spaces or can be perceived by a listener as airborne sound (Barron, 1993). Fig. 2.23 illustrates some possible path in which sound can transmit through the floor, where all the components are rigidly connected (i.e. Flanked transmission). Arrowhead marked with letter D–Represent direct transmission through the common petition. While arrowhead marked with letter F–Represent flanking paths (Harris, 1994).

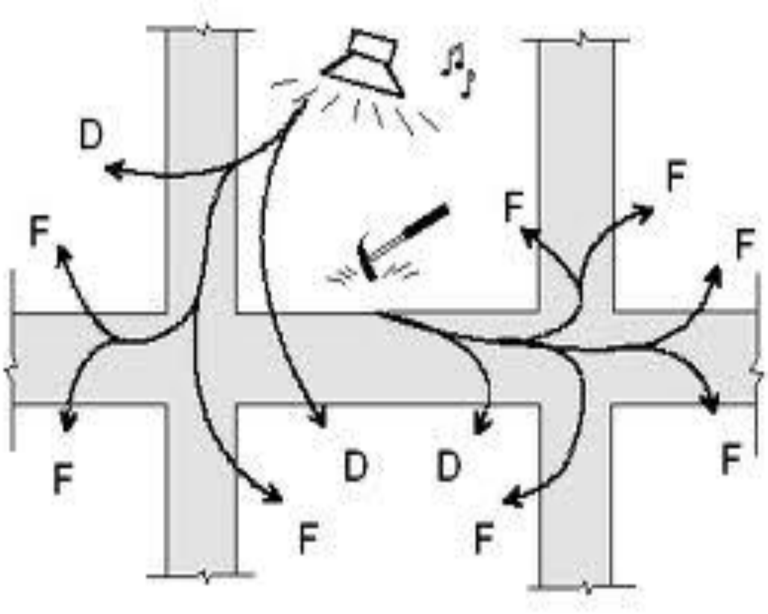


Fig. 2.23: Positive part of transmitted sound through a structure of a building (Harris, 1994).

Once a sound has entered a structure and is propagating as vibration, it can travel for considerable distances; "the energy lost in traveling from one side of the building to the other depends on the material and on the detail of the construction" (Harris, 1994). A source that is rigidly connected to the building structure will be heard more easily in adjacent spaces than a source that is resiliently connected or rest on a resilient pad. As shown in figure 2.24a and 2.24b, flanking paths can be reduced to minimal by introducing structural breaks such as isolation joint and resilient connections in the construction (Harris, 1994: Green Glue Company LLC, 2006).

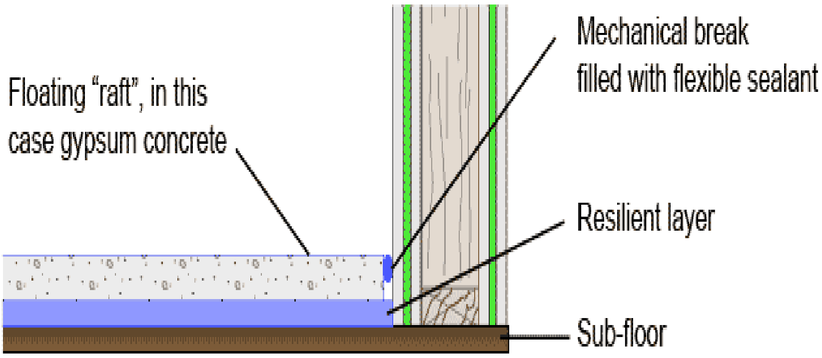


Fig. 2.24a: Floating floor using a layer of resilient material to attenuate impact noise (Green Glue Company LLC, 2006).

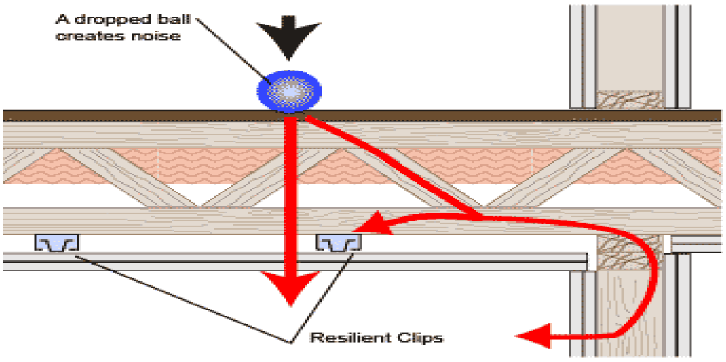


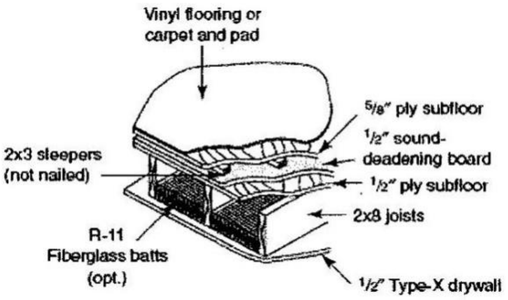
Fig. 2.24b: The use of resilient clips on floor (Green Glue Company LLC, 2006)

On this background, considering the rating impart sound insulation will help in understanding the basic principle of impact insulation class (IIC) ratings for various types of floor and ceiling constructions.

a) **Impact insulation class (IIC)**: This is known as a ‘single-number’ impact isolation rating for floors or ceiling construction, which is similar in Intent and derivation to STC walling ratings. Test of impact insulation class (IIC) for different types of floor or ceiling construction are made with a standard tapping machine and noise level are measured in 1/3-octave bands, which are then plotted and compared to a standard contour, approximately as with the sound transmission class (STC). From practical sense, the higher the impact noise insulation class (IIC) rating, the greater the impact noise insulation provided by the construction (Bliss, 2005). See table 2.6 for STC and (IIC) rating for typical walls/ceiling assemblies.

Table.2.6: STC and IIC ratings for typical walls/ceiling assemblies

<table>
<tr><td colspan="3">Floating floor
2×8 joists, $1/2$ ″plywood subfloor, $1/2$ ″ sound deadening board nailed to subfloor, 2 × 3 furring strips (unnailed), $5/8$ ″ plywood subfloor, Type-X dry wall ceiling.</td></tr>
<tr><td>Variation</td><td>IIC</td><td>STC</td></tr>
<tr><td>Add vinyl, flooring R-11 fiberglass batts</td><td>49</td><td>52</td></tr>
<tr><td>Add Capet and pad, R-11 fiberglass batts</td><td>68-78*</td><td>51</td></tr>
<tr><td colspan="3">*Note: low-pile carpet on fiber pad lowest. High-pile on thick foam pad highest</td></tr>
</table>



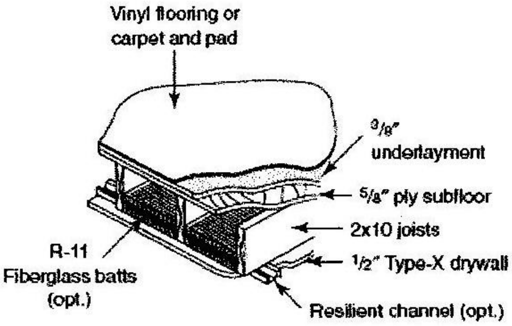
Floating floor

Wood floor

2×10 joists, $^{5}/_{8}$ ″plywood subfloor, $^{3}/_{8}$ ″ particleboard underlayment. $^{1}/_{2}$-inch, Type-X dry wall ceiling.

Variation	**IIC**	**STC**
Add vinyl floor covering	38	38
Add vinyl, R-11 fiberglass batts and resilient channels	49	50
Add carpet and pad	50-60*	40
Add Capet and pad, R-11 fiberglass batts and resilient channels	63-73*	53

*Note: low-pile carpet on fiber pad lowest. High-pile on thick foam pad highest



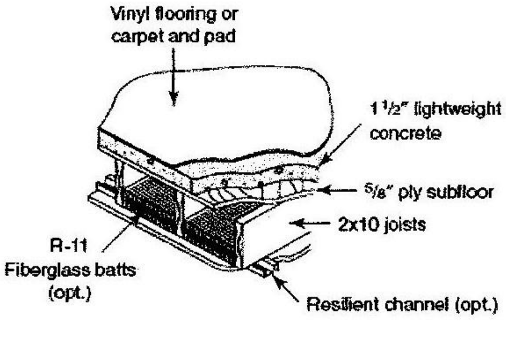
Wood floor

Lightweight concrete floor

2×10 joists, $^{5}/_{8}$ ″plywood subfloor, $^{3}/_{8}$ ″ particleboard underlayment. $^{1}/_{2}$-inch, Type-X dry wall ceiling.

Variation	**IIC**	**STC**
Add carpet and pad	50-59*	47
Add Capet and pad, R-11 fiberglass batts and resilient channels	64-74*	58
Add vinyl, flooring R-11 fiberglass batts and resilient channels	47	50

*Note: low-pile carpet on fiber pad lowest. High-pile on thick foam pad highest



Lightweight concrete floor

[Source: Bliss, 2005]

2.6.3 Impact sound transmission

Impact sound transmission is when there is a contact with the structure, which then travels through the structure due to the physical excitation on the structure floor or wall by impacts from footfall, moving furniture and dropped items, as illustrated in figure 2.25, although it is governed by a completely different set of values than airborne sound (Means, 2009).

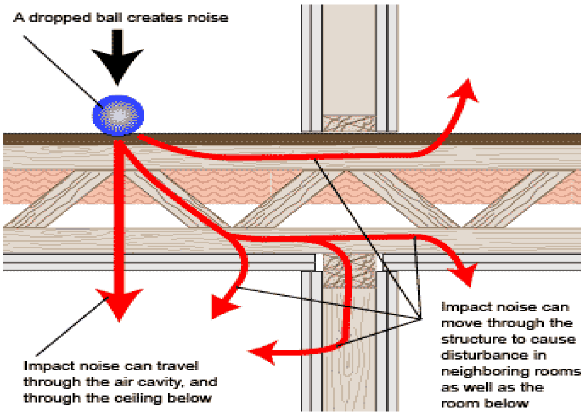


Fig. 2.25: Impact noise transmission (Green Glue Company LLC, 2006)

2.7 Acoustical sound absorbing materials

In a practical sense, all building materials have abortive capacity, some are low and others have relatively high abortive capacity. For example, upholstered furniture, curtains, textiles, and even humans often contribute to the total amount of abortion in a particular space or structure, which is known as natural abortion. Since natural absorptive materials are not sufficient or enough, there is need for the introduction of high performance sound absorbers. For instance, material like soft wood paneling will absorbed noise or sound than concrete, likewise fabric materials like window blind furniture can act as a good in a structure.

Sound absorption is classified into two main categories such as: “Porous and resonant (membrane and cavity resonators) absorption” (Cox and D’Antonio, 2004).

2.7.1 Porous absorption

Porous absorption are obtained from materials that have an open pore structure or open air-filled pores, such as porous fireboards, mineral wool, textile materials etc. In a practical sense, porous abortion coefficient increases with frequency. Porous materials are very effective for the suppression of noise in structure, since there are acoustically very effective due to the open surface. If the thickness of absorber is less than one fourth (1/4) of the wavelength, then there will be little effect, likewise the maximum effect is obtained when the displacement to the wall surface from the centre of the absorber is equal to one fourth (1/4) of the wavelength and is restrained to a comparatively narrow frequency band. It implied so because the maximum particle velocity of the incident and reflected waves will occur within the porous materials (Mechel, 2001).

2.7.2 Resonant absorption

Resonant absorption is obtained by energy losses in an oscillating system, and does not depend on the properties of the material like porous absorption. Resonant absorption coefficient does not increase with frequency but has its maximum around a determine frequency known as the resonance frequency. The resonant absorption is of two main types, the cavity (Helmholtz) and membrane resonators (Cox and D’Antonio, 2004).

a) *Cavity (Helmholtz) resonator*: This is known as a single cavity resonator which comprises of an enclosed air volume connected to the room by a narrow opening. A typical example of cavity resonator is a bottle, where the enclosed air volume is the wide path and the bottleneck is the narrow opening.

The air in the opening (i.e. the neck) of cavity resonator is set into motion when sound wave strikes it, and is also same for membrane resonator, only that small air volume oscillates on top of the bigger air volume. The absorption of a cavity absorber centered to a narrow frequency band known as resonance frequency, although calculation of the resonance frequency is more complicated (Mechel, 1994). Helmholtz or cavity absorber curve is shown in figure 2.26.

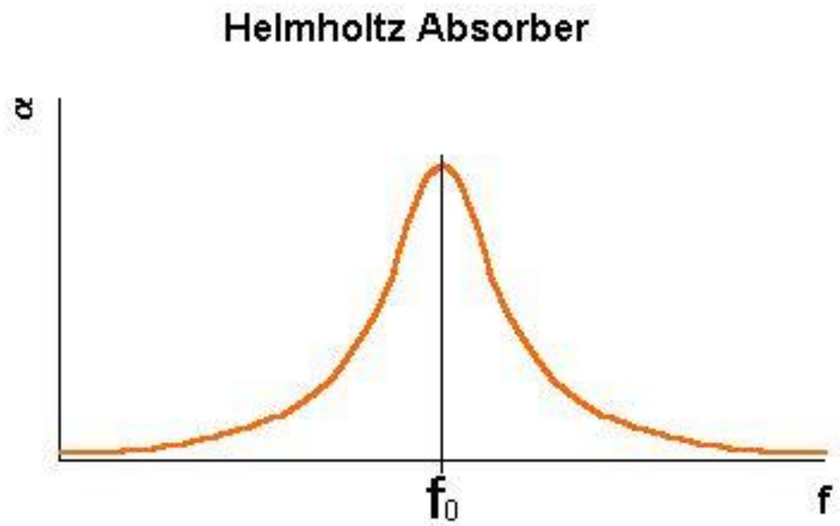


Fig.2.26: Helmholtz absorber curve [Cox and D'Antonio, 2004]

The frequency resonance (f_0), for cavity resonator can be calculated with the formula below:

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{s}{v\left(I + \frac{\pi}{2}b\right)}}$$

Where,

$f_0 =$ Resonance frequency (Hz)

$C =$ speed of sound (340m/s)

$S =$ neck opening area (m2)

$\mathrm{V} =$ volume of the void (m3)

$\mathrm{I} =$ depth of the neck

$\mathrm{b} =$ radius of the neck opening

A cavity resonator is not necessarily an individual unit, perforated panels and slotted absorbers also serve same purpose as cavity resonator, where all the three perimeters are combined, which may be plywood, hardboard, plasterboard or metal, and can also behave like membrane absorber. Mostly commercially used absorptive materials falls under this category. The absorption of a perforated panel at a displacement from a rigid wall with mineral wool in the void will vary with respect to the open space. Figure 2.27, shows different degrees of perforation of a hard fibre panel (Bies and Hansen, 1996).

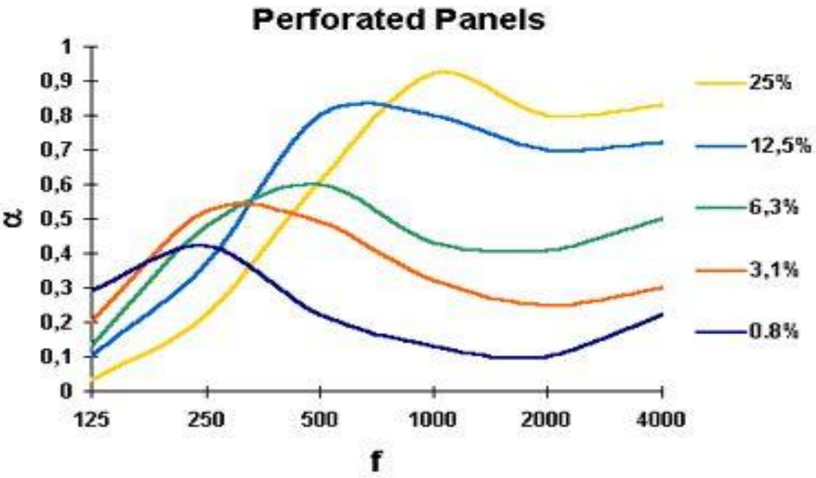


Fig.2.27: Curves for different degrees of perforation of a hard fibre panel [Cox and D’Antonio, 2004].

2.7.3 Membrane absorption

Membrane resonator is thin, solid panels that are normally efficient for the absorption of low frequency sound. “Membrane resonator is either flexible sheet stretched over supported or rigid panels, although both at a displacement from a rigid wall with an enclosed air volume in between them” (D’Antonio, 2008). Membrane absorbers are mostly used in spaces intended for music or rooms with special low- frequency noise problems, to balance the natural high frequency absorption. Unlike other resonators, membrane absorber coefficient reaches its maximal at the resonance frequency (f_0), as illustrated in figure 2.28 (Mechel, 2001, Cox and D’Antonio, 2004).

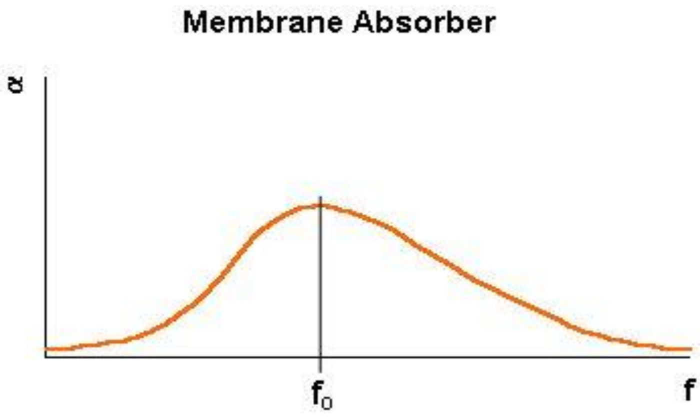


Fig.2.28: Membrane absorber curve [Cox and D’Antonio, 2004]

The frequency resonance (f_0), for membrane absorption can be calculated with the formula below:

$$f_0 \approx \frac{60}{\sqrt{md}}$$

Where,

f_0 = Resonance frequency (Hz)

m = mass by surface (kg/m^2)

d = displacement between membrane and rigid wall (m)

2.7.4 Absorption coefficient

According to (Bies and Hansen 2009), “the absorption coefficient of a material is used to express the capacity of a particular material to absorbed sound, although some of the materials have low capacity and other have high capacity depending on the type of material”, as shown in table 2.7. Energy is transformed from kinetic energy of sound wave into thermal energy and some of the energy is always reflected. Mathematically, absorption coefficient (α) is expressed as:

$$\alpha = \frac{\text{transmitted} + \text{aborbed energy}}{\text{total incident energy}}$$

Table. 2.7: Selected sound-absorption coefficient of various building materials

TYPICAL DATA/MATERIAL	**125Hz**	**250Hz**	**500Hz**	**1000Hz**	**2000Hz**	**4000Hz**	**NRC**
Marble	.01	.01	.01	.01	.02	.02	.00
Gypsum board, ½ in	.29	.10	.05	.04	.07	.09	.05
Wood, 1 in thick, with air space behind	.19	.14	.09	.06	.06	.05	.10
Heavy carpet on concrete	.02	.06	.14	.37	.60	.65	.30
Acoustical tile, surface − mounted	.34	.28	.45	.66	.74	.77	.55
Acoustical tile, suspended	.43	.38	.53	.77	.87	.77	.65
Acoustical tile, empty, painted (est.)	.35	.35	.45	.50	.50	.45	.45
Audience area, empty, hard seats	.15	.19	.22	.39	.38	.30	.30
Audience area, occupied, upholstered seats	.39	.57	.80	.94	.92	.87	.80
Glass fiber, 1 in.	.04	.21	.73	.99	.99	.90	.75
Glass fiber, 4 in.	.77	.99	.99	.99	.99	.99	.95
Thin fabric, stretched tight to wall	.03	.04	.11	.17	.24	.35	.15
Thick fabric, bunched 4 in, from wall	.14	.35	.55	.72	.70	.65	.60

[Source: Ramsey, C., et al. ,2000]

2.8 Speech Intelligibility

Research has shown that in today’s multi-media society, speech in all likelihood is the most significant and effective in terms of individual communication. More emphasis has been led on the intelligibility and clarity of public address (PA) system. Systems with good intelligibility can be transformed into total unintelligibility. “However, with many rooms being used exclusively for speech between individual and groups, it is essential that acoustic design accommodate and enhance such use” (Dorman, et al).

Marsh (2002), delineated “speech intelligibility as the degree to which a normal listener or human can understand a spoken message or phrase”. If the residents are unable to understand the emergency information they are being given, they cannot react appropriately, as a result which may lead to injury or death. Background noise, echoes, reverberation and distortion are the primary causes for low speech intelligibility (e.g. sound from amplifier, speaker etc) (Houtgast. et al., 1985). Late sound is strongly influenced by the reverberation time; longer reverberation times produce a higher level of late sound and thus undermine speech intelligibility. “Speech intelligibility is very important because many activities rely on verbal communication to a greater or less extent, for example, in large auditoria or where public talk is being given, a listener has limited access to a spoken word or phrase but solely rely on depend more heavily upon the sound actually produced by the speakers month” (Houtgast. et al., 1985).

Communication systems normally compress speech into less than the usual bandwidth and may reduce the dynamic range, so alternative analysis methods are used.

The frequency range and acoustic power of speech vary widely. Consonants in normal speech have a power of around 0.03μW, while shouting can produced up to 2mW. The information content of speech is mainly carried by high –frequency low–energy consonants. Noise has the greatest masking effect on speech if it contains significant power over 500Hz. Low- frequency background sound is more acceptable than high- frequency sound except that low-frequency (500 Hz) pure tones have a strong masking effect. "A widely accepted standard way of assessing the problem is to use speech interference levels(SIL), known as the arithmetic average of sound pressure level at 500, 1000 and 2000Hz frequencies, however, is measure of the degree to which background noise interferes with speech" (Marsh, 2002). The upper limiting SIL-values for the indicated voice levels are approximately shown in table 2.8. Above these values, the speaker will attempt to raise his or her voice for listeners to hear him or her (Turner and Pretlove, 1991).

Table. 2.8: Approximate SIL values in (dB) for various voice levels

Voice level	Upper Limit SIL(dB)
Loud	62
Max. shout	77
Normal (private)	47
Normal (public)	52
Raised	57
Relaxed	42
Shouting	72
Soft	37
Very loud	67
Whispering	32

[Source: Marsh, 2002]

In an enclosed space, speech transition is influenced by the signal-to- noise ratio (background noise such as that from machinery), just as it is in the open air. For instance, a noisy ventilation system can easily make speech difficult to understand. But the reflection characteristics of a room need also to be considered. As well as early reflections which are desirable for speech communication, there will be late reflections which reduce intelligibility. In the extreme situation of a cathedral space with a long reverberation time, the late reflections render speech incomprehensible at all but short distance from the speaker (Barron, 2009). For good intelligibility to be achieved, a high early energy fraction is necessary, requiring high early energy and low late energy.

2.8.1 Requirement for good speech intelligibility

According to (Howard and Angus, 2009), for good intelligibility to be attain we require the following.

1. The direct sound should be greater than or equal to the reverberate sound, which implies that the listener should not be further away from the critical distance.
2. The speech to interference ratio should ideally be greater than 10dB and at worst 7.5dB.
3. The previous two requirements (1) and (2) above have the implication that the level of the direct sound should be above a certain level (at least 10dB above background noise and equal to the reverberant sound level), “for both efficiency and the comfort of the audience, since the direct sound is to be constant at this level throughout the coverage area” (Howard and Angus, 2009).

2.8.2 Key Parameters affecting speech intelligibility

The key parameters affecting speech intelligibility in an enclosed space or hall are reverberant (direct-to-reverberant) or late energy, early sound reflection, signal-To-Noise Ratio, frequency response and lastly, ambient or background noise.

2.8.2.1 Reverberant (direct-to-reverberant) or late energy

“The reverberant sound field consists of sound waves that have been reflected from multiple surfaces before they arrive at the listener’s ears” (Templeton, 1997). They travel long distances between reflections and therefore are progressively reduced in loudness from the direct sound and early reflections. The reverberant sound field may persist for 2 sec or longer in concert halls. It contributes to sensations of reverberance. If the reverberant sounds arrive from many directions and are not exactly the same at the two ears of people listening, it will also increase the sensation of acoustic spaciousness in the room.

If the reverberant sound field has strong low-frequency or bass components, it will increase the sense of warmth in the room. If it has strong higher frequency or treble components, it will contribute to the perception of brilliance (Johnson, 1990). The required ratio of direct-to-reverberant signal for intelligible speech is highly dependent on the overall reverberation time of the space. For example, a much higher ratio is required in a cathedral with a reverberation time of say 7 s, than a similar-sized building with an RT of only 2 or 3 s. It is interesting to note, as will be shown later, that good intelligibility can be obtained even with negative D/R ratios (Templeton, 1997).

2.8.2.2 Early sound reflection

“The early sound reflections are sound waves that strike one of the room surfaces and are reflected to the listener’s location”. Reflections that arrive within short time intervals after the direct sound (less than 80 msec for music) are usually combined with the direct sound by the ear, see figure 2.29. These reflections add to the direct sound increasing its apparent loudness. If the reflections arrive within 40 msec or less after the direct sound, they will also contribute to a sense of acoustic intimacy. Early reflections that arrive from the sides of the listener’s head also contribute to sensations of envelopment and widening of the acoustic image of the sound source. The combination of these early reflections with the direct sound is what makes it possible to have similar levels of loudness at seats located throughout a large room (Bradley, 1986).

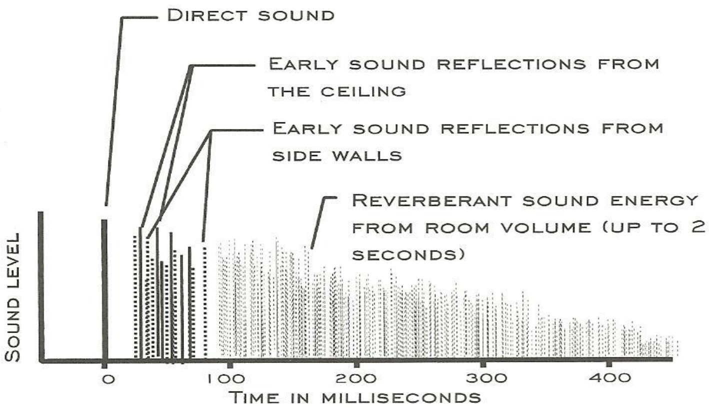


Fig. 2.29: "Impulse response in a room showing direct sound, early sound reflections, the later or reverberant sounds, and the ambient or background noise" (Cavanaugh and Wilkes, 1999).

2.8.2.3 Signal-To-Noise Ratio

"Speech intelligibility in a room or hall depends on the degree of speech relative to the degree of background noise. Speech must dominate over background noise, for it to be heard by a listener, such as that from machinery, traffic or people, can adversely affect speech intelligibility by masking the necessary higher frequency component" (Bartlett and Bartlett, 2009). "A convenient and easily determined indicator or index number of speech intelligibility in a room is named the signal- to-noise ratio. It implies that the greater the speech intelligibility, the larger the SNR" (Bartlett and Bartlett, 2009).

The formula for calculating SNA according to (Marsh, 2002), is the difference between the A-weighted long-term average level ($\mathrm{L_{SA}}$) and the A-weighted long-term average level background noise ($\mathrm{L_{NA}}$), measured over any particular condition or time, which implies that:

$$\mathrm{SNA} = \mathrm{L_{SA}} - \mathrm{L_{NA}}$$

Research has shown that “when a room is having a signal-to-noise ratio of less than 10dBs; speech intelligibility becomes significantly a problem for people with average hearing” (Kleiner, 1980). “To assure that children with hearing damages and language disabilities are able to achieve high speech intelligibility, the American speech- language hearing association advocates an SNR of at least +15 dBs” (Wilson, et al., 2002). The signal-to- noise ratio required depends heavily on the spectral content or frequency make-up of the noise. The effect has been extremely well researched and a standardized method of assessing the degree of intelligibility from a given noise spectrum and level can be used, as shown in figure 2.30.

The absolute level of speech signal must also be considered, which implies that a little above +15bB add up to the improvement in intelligibility, whereas at levels much over 90dB, the intelligibility begins to decrease (Marsh, 2002).

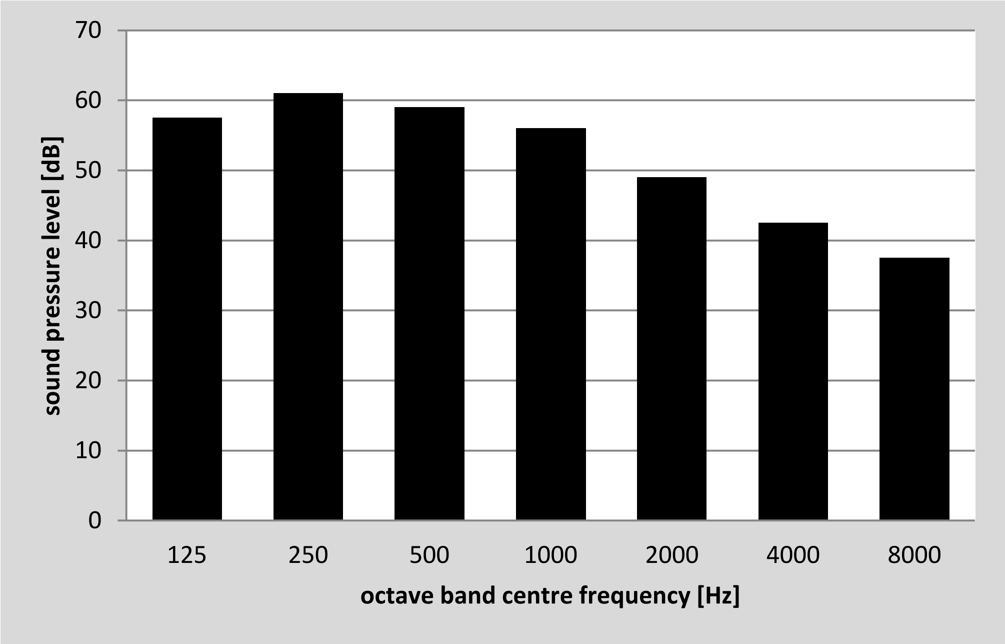


Fig. 2.30: Average frequency spectrum for normal speech (adapted from Templeton, 1997)

2.8.2.4 Frequency response

Although the primary speech information is contained at higher consonant frequencies, the main power of the voice comes from low and mid frequency vowel sounds with most energy centered at around 200-600 Hz. Typically the higher frequency information is 15-20 dB below these levels can be easily masked or lost if the sound system places too much emphasis on the lower frequency region as often happens when systems are either incorrectly equalized or worse still not equalized at all (Bartlett and Bartlett, 2009).

2.8.2.5 Ambient or background noise

Shih, (1991) augured that “noise is a complex sound that has little or no periodicity and thereafter states that the essential characteristic of noise is its undesirability”. On the other hand, “noise is defined as unwanted sound” (Salvato, 1982). “In recent years, the rapid increase of noise level in our environment has become a national public health hazard; people are usually annoyed by noise and can be distracted by it. Noise affects man's state of mental, physical, and social well-being” (Shih, 1991). For these reasons, there is need to achieve quiet conditions in multiple dwelling housing, offices, factories and multipurpose spaces.

Therefore, “ambient sound or noise is the composite of airborne sound from many sources near or far associated with the environment, although no particular sound is signed out for interest, for example it might be noise from machinery or traffic” (Pelton, 1993). However, whether we are in our homes, workplaces, or outdoors, we will almost certainly be exposed to a certain level of background or ambient sound such as traffic noise, railway noise or aircraft noise. The main contributor to background noise is usually the ventilation systems.

Ventilation systems generate noise due to fan noise and noise generated by the air-flow itself. Before we can begin to solve a noise control problem, we must determine how much background sound is acceptable (Turner and Pretlove, 1991). Very low level background sound can even contribute to sleep or rest when not interrupted by intermittent or sudden loud noises in some public places, a somewhat higher level of background sound may be acceptable. Other places, such as auditoriums and concert halls where very low background sound level are required, present particular problems in sound control (Egan, 1988). Figure 2.31 shows the Noise Criteria (NC) curve, indicating the NC for different sound pressure level in dB.

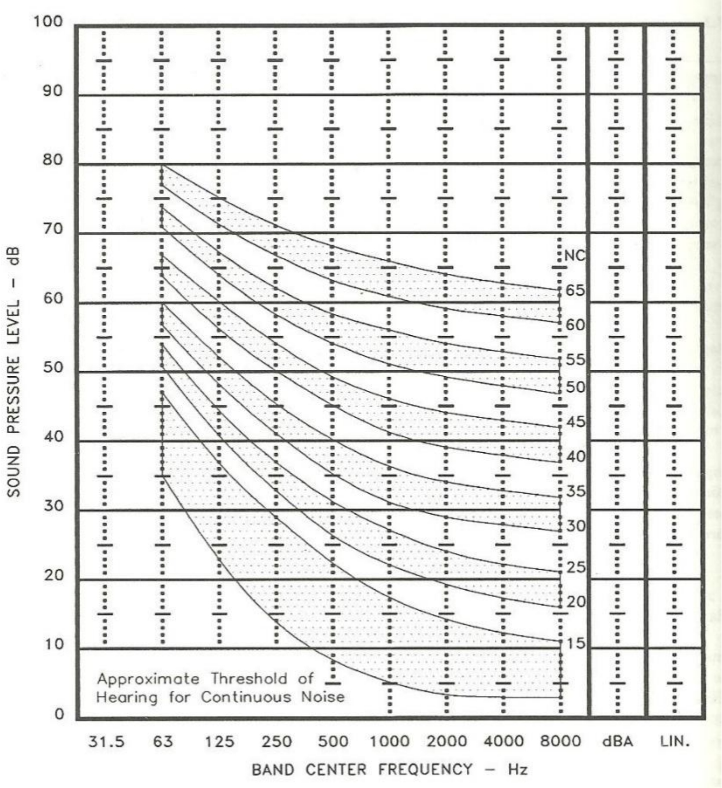


Fig. 2.31: Noise Criteria (NC) curve, (Beranek, 1960, Pelton, 1993).

According to measurements by (Kleiner, 1980), the noise generated by the audience in a typical concert hall could reach NR25, that is 10 db greater than the recommended criterion, as shown in figure 2.31 and table 2.9.

Several criteria are available for background noise, which are based on individual octave band sound levels. The most common European criterion is the NR (Noise Rating) but there is also the American NC (Noise Criterion), a revised version the PNC (Preferred Noise Criterion) and more recently the RC (Room Criterion).

Noise Criteria (NC) curves are one of several systems used to establish allowable sound levels for various interior spaces. NC curves are shaped to compensate for the human ear's response to loudness at octave band center frequencies and the speech interference properties of noise. Acceptable NC levels for various types of rooms are given in table 2.9 (ASHA, 2000).

Table. 2.9: Recommended NC Values and the approximate continuous sound levels for building interiors.

Type of Space	Recommended NC value	Approximate dB value
Office Building:		
Open plan office	30 – 40	38 – 48
Private office	25 – 35	33 – 43
Lobbies, public areas	35 – 40	43 – 48
Churches	25 – 35	33 – 38
School:		
Classroom	30 – 35	48 – 43
Cafeterias	35 – 40	43 – 48
Multipurpose spaces	30 – 35	38 – 43
Indoor Gymnasium	40 – 50	43 – 58
Performing arts spaces:		
Auditorium and Theaters	25 max.	33 max.
Music practice rooms	35 max.	43 max.

(Source: Mehta et al, 1998)

The choice of an acceptable NC rating for design purposes depends on the type of space use within a building that is being considered. For example, in a private office or conference room environment, “the primary consideration is to ensure that the background noise (with the HVAC system in operation) does not interfere with speech communication; in open-plan offices, however, it is also important to ensure that the background noise is high enough to reduce the awareness of speech and other noises produced by neighbors nearby” (Walter et al, 2009).

In contrast, in a concert hall, the primary consideration is to ensure that the background noise (with the HVAC system in operation) does not “mask” (i.e., prevent one from hearing) the quietest passages of music. “It should be emphasized that meeting an NC criterion does not ensure that the “quality” of the background noise will be unobjectionable to a listener (as a result of spectral imbalance) unless the shape of the noise spectrum being evaluated is approximately that of the designated NC curve for at least four contiguous octave bands” (Harris, 1991).

On the other hand, due to the recognized shortcomings of the NC curve, specifically that they are undefined in the very low frequencies (16 and 31.5 octave bands) and are not sufficiently stringent at frequencies above 2kHz. ASHRAE (the American society of heating, refrigerating and air-conditioning engineer) developed and adopted the **room** criterion (RC) as the suggested noise limiting benchmark in preference to NC curves and this curves were used to evaluate the acceptability of background mechanical system noise for typical space types (Walter et al, 2009). Room criteria curve is shown graphically in figure 2.32.

Region A: “High probability that noise-induce vibration in light wall and ceiling construction will be clearly feelable; anticipate audible rattles in light fixtures, doors, window etc” (Walter et al, 2009).

Region B: "Noise-induced vibration in light wall and ceiling construction may be moderately feeable; slight possible of rattles in light fixtures, doors, window etc" (Walter et al, 2009).

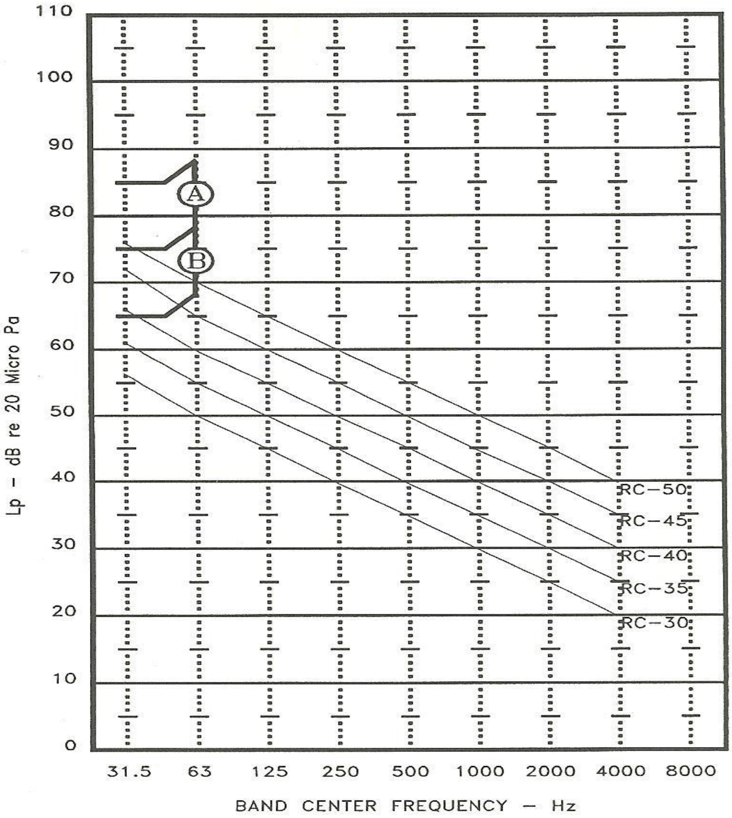


Fig. 2. 32: Room criteria (RC) curve, (ASHRAH handbook, 1991)

RC system allows for the noise to be classified as neutral, rumbly, or hissy because rumbly and hissy environments, typically caused by the mechanical system, can create annoyance for the occupants even if the noise level falls within the recommended NC value for that type of space (Mehta et al, 1998).The recommended RC Values and the approximate continuous sound levels for building interiors are shown in Table 2.10.

Table. 2.10: Recommended RC Values and the approximate continuous sound levels for building interiors.

Type of Space	**Recommended RC value**	**Approximate dB value**
Office Building:		
Open plan office	35 – 40	43 – 48
Private office	25 – 35	33 – 43
Lobbies	35 – 45	43 – 48
Churches	25 – 35	33 – 38
School:		
Classroom	35 – 40	43 – 48
Cafeterias	40 – 45	48 – 53
Multipurpose spaces	35 – 40	43 – 48
Indoor Gymnasium	45 – 50	48 – 58
Performing arts spaces:		
Auditorium and Theaters	25 max.	33 max
Music practice rooms	35 max.	43 max.

Source: (Mehta et al, 1998)

Room criteria (RC) curve differ from noise criteria (NR) curve in a number of aspects which was summarized by (Walter et al, 2009) as:

1. They are straight lines, as in figure 2.32.
2. Their slope is constant at -5dB per octave (determined from extensive tests, mostly in the range of 40 to 50 dB).
3. Region labeled A and B as in figure 14 deal with the problem of low frequencies and high sound pressure level, an issue that cannot be discovered in the noise criteria (NC) curve. Theses region deals with rumble and vibration that can cause extremum annoyance to many occupants as illustrated in figure 2.32 above.

2.9 Speech intelligibility measurement techniques

The basically two types of tasks that have been used to measure speech intelligibility are categorized in to two major outlines:

1. Word identification tests in which the listener is required to write down what the talker says. In order word, known as subjective testing".
2. Scaling procedures in which the listener makes judgments about the talker's intelligibility using a technique such as an equal appearing interval scaling procedure or direct magnitude estimation. It is an accurate and rapid method of measuring intelligibility with acoustic instruments.

2.9.1 Articulation index

The articulation index is an existing method for rating the effect of background noise on speech intelligibility which was adopted from an American Standard (ANSI 53.5). Basically the signal-to-noise ratio between the speech signal and the background noise in each of 20 one-third octave bands is measured. The 20 S/N ratios are then individually weighted according to the speech information content contained within a given band. The weighted values are then combined to give a single overall value referred to as the articulation index (AI). The method in fact operates using the rms levels of speech peaks, a (+12) dB correction factor being adopted to convert the long-term rms speech level to the equivalent short-term peak level. Other corrections are also made for very high background noise levels (above 80dB) where the effect of masking is more marked. The masking effect of one frequency band on another is also corrected for. It is interesting to note that the method assumes that at S/N ratios of 30dB or more, no masking of the wanted signal by the noise occurs (Templeton, 1997).

The Al uses a linear scale from 0.0 to 1.0 where 0.0 is total unintelligibility and 1.0 is equivalent to 100% intelligibility and based its calculation on the signal to noise rations in the five octave bands with centre frequencies of 0.25, 0.5, 1.2, and 4 KHz (Marsh, 2002). Although a generalized subjective response scale can be formulated for example as shown in table 2.11 below.

Table. 2.11: Articulation index scale

AI	Unacceptable	marginal	Acceptable/ fair	good	Very good	excellent
	$0.2 <$	$0.2 - 0.3$	$0.3 - 0.4$	$0.4 - 0 - 6$	$0.6 - 0.7$	> 0.7

Source: [Templeton, 1997- Acoustic in the build environment advice for the design team]

The formula for calculating articulation index (AI) is given by:

$$\mathrm{AI} = \frac{\mathrm{G[i]}}{30\mathrm{dB}} = \sum_{\mathrm{i}=1}^{5} (\mathrm{Lsa} - \mathrm{Lna} + 12)\ \mathrm{dB}$$

Where $\mathrm{G_{[i]}}$ denotes the weighing factor for each octave band, as shown in table 2.12. However, for the calculation to be done “three basic procedure most be consider which includes measurements for the effective signal-to-noise ratio for each octave band, applying a weighting factor to each ratio and lastly, clipping to ensure that maximum contributions occur at +18Db and minimum at -12dB” (Marsh, 2002).

Table. 2.12: Weighting factors for different frequencies

Frequency in (Hz)	250	500	1000	2000	4000
Weighing factor ($\mathrm{G_{[i]}}$)	0.072	0.144	0.222	0.327	0.234

[Source: Marsh, 2002]

2.9.2 Subjective testing

A number of procedures are available for objectively testing the intelligibility of a sound system using live listeners, for example, phonetically-balanced word lists are used, read out either implanting the test word in a non-contextual carrier sentence so as to excite room reverberation or as individual and separate words with an appropriate spacing between them. “The words are then either ticked off on a multiple answer sheet or written down as they are heard. The percentage intelligibility is then calculated by determining the number of correct answers and expressing this as a percentage” (Templeton, 1997).

2.9.3 Percentage articulation loss of consonant % Alc

Direct percentage Alcons (percentage loss of consonants) testing, although based on concepts dating back to the 1960s and early l970s, is a relatively new measurement technique which is originally based on the reception of words by listeners (Bruel and Kjar magazine, 2008). Essentially this method measures the ratio between early energy, late energy, noise and the ratio of the direct to reverberant sound components received from a sound system or test loudspeaker at a typical listening position. The measurement is usually carried out in the 2 kHz band only and requires the use of a highly sophisticated and computerized instrument, although measurements at other frequencies are often carried out to give a more detailed picture of a particular system (Ballon, 2009).

The % Alcons is obtained by measuring the RT and the direct-to- reverberant (reflected energy) ratio and from these two parameters the equivalent % Alcons can be computed.

One of the most useful features of the % Alcons method is that one can correlate measurement with prediction, and the % Alcons is still effectively the only method we have of predicting the potential intelligibility of a sound system before it is installed. “In Dirac, the % Alc is derived from the STI through a widely used approximation formulation by Farrel Becker” (Houtgast and el at, 2002).

$$\% \, Alc = 170.5405e^{-5.419(STI)}$$

The % Alc scale is not quite sophisticated; the concept works more as series of bands, as shown in table 2.10.

2.9.4 Speech transmission test (STI and RASTI)

“Speech transmission index (STI) is a more new and detailed version of the articulation index first introduced by Steeneken and Houtgast as a measure of estimating speech communication from acoustic measurements” (Steeneken and Houtgast, 1983). Speech transmission index, are the modern and most complex intelligibility measurement techniques currently available. It is only the advent of modern microprocessor and desk top computer technology that have enabled the technique to be implemented on a practical basis (Bruel and Kjar magazine, 2008). This method of measurements surpasses the (AI) concept due to the attempt made in including distortion in the time domain, and those that occur over time, like reverberation. Some degree of reverberation adds ‘liveness’ to a room, but substantial reverberation is very common problem that causes speech intelligibility to deteriorate (Marsh, 2002: Gelfrand, 2009).

The STI uses a sophisticated method of physical analysis known as the modulation transfer function (MTF) to determine how a test signal is affected by a noise and distortion in the octave bands from 125 to 8000Hz. The MTF results are then converted to a transmission index for each band. The bands are weighted according to their importance for speech communication (as in the case of AI), and are then combined to produce the STI, which ranges from 0 to 100% (or 0 to 1.0), and is divided into five (5) categorized bands from ‘bad’ to ‘excellent’, as shown in table 2. 13. The higher the STI, the better are the conditions for speech communication (Gelfrand, 2009).

Table. 2.13 : STI/RASTI and % ALcons intelligibility scale

STI/RASTI	0 − 0.3	0.3 − 0.45	0.45 − 0.6	0.6 − 0.75	0.75 − 1.0
	Bad	Poor	Fair	Good	Excellent
%ALcons	100 − 33%	33 − 15%	15 − 7%	7 − 3%	3 − 0%

[Source: Templeton, 1997]

This method, was originally intended for assessing natural speech intelligibility in auditoria, whereas is arguable that a different expectation and consequent scaling might apply to that for general paging system at a train station for example. Despite this, the method has been widely adopted within Europe to evaluate and set the design criteria for a wide range sound system ranging from emergency PA system in public buildings, shopping centers, football stadia, transportation terminals and concert hall/theatre auditoria (Borwick, 2001).

From the above it can be deduced that the formula for calculating STI is given by:

$$\mathrm{STI} = \left(\frac{\mathrm{SNR} + 15}{30\mathrm{dB}}\right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. \text{(i)}$$

Where SNR is signal-to-noise ratio is translated by:

$$\mathrm{SNR} = 10\log\frac{\mathrm{m(F)}}{1 - \mathrm{m(F)}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.\dots \text{(ii)}$$

And $m(F)$ is the modulation index given by:

$$\mathrm{m(F)} = \frac{\sum_n \frac{a_n \exp\left(-j\pi F \frac{r_n}{c}\right)}{r_n^2}}{\sum_n \frac{a_n}{r_n^2}} \dots\dots\dots\dots.\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. \text{(iii)}$$

Therefore, $m'(F)$ is known as the modulation index given by the function below when modified:

$$\mathrm{m}'(\mathrm{F}) = \mathrm{m}(\mathrm{F}) \frac{\mathrm{I_S} \sum_{\mathrm{n}} \frac{\mathrm{a_n}}{\mathrm{r_n^2}}}{\mathrm{I_S} \sum_{\mathrm{n}} \frac{\mathrm{a_n}}{\mathrm{r_n^2}} + \mathrm{I_n}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots(\mathrm{iv})$$

“From the above formulas, in (ii), (iii) and (iv) *F* represents the modulation frequency, in (iii) *C* is the speed of sound and refers to the With r_n being the relative path length of the n$^{\text{th}}$ impulse and I_n as the intensity of background noise.

On the other hand, rapid speech transmission Index (RASTI), is a portable method used in the real-time determination of speech intelligibility developed by Steeneken and Houtgast and can be established by using instrumentation which include a loudspeaker place in the location of the a talker or speaker and microphone placed where the listener or hearer would be (Steeneken and Houtgast, 1985). The loudspeaker presents a test signal into the room being evaluated, and the sound picked up by the microphone reflects how the original test signal has been affected by the noise and other acoustical characteristics in the room. The result are then passed as RASTI values from 0.0 to 1.0, which can be used to indicate relative speech intelligibility: for instance, ≤ 0.29, is rated as bad; 0.3 to 0.44, rated as poor; 0.45 to 0.59, rated as fair; 0.6 to 0.74 as good; ≥ 0.75, excellent (Gelfrand, 2009), as also indicated in table 2.10.

2.9.5 Merit and demerit of the (STI/RASTI) system

1. It automatically takes into account any background noise and hence the prevalent S/N ratio as well as the effect of reverberation time and reverberant level (i.e. D/R ratio) (Gelfrand, 2009).

2. However, like the % Alcons methods, the STI does not account for discrete, late reflection. System non-linearities and some forms of signal processing can also severely disrupt this method (Marsh, 2002).
3. A major advantage of STI /RASTI is the ability to readily carry out ‘what if’ speculations and predictions by post-processing the noise component data; for example, if measurements were taken during a quiet period, it is possible to manually input new noise data and get a recalculated STI (Crandell and el at, 2005).
4. A major disadvantage of the RASTI method is that no information is gathered over the whole operating range of a sound system, e.g. at 125 and 250Hz at low to mid frequencies and at 4 and 8kHz at the upper end (kang, 2002).
5. The disadvantage of RASTI/STI method is that the potential result cannot be readily predicted without the use of a complex computer model (Walter et al, 2009).

2.9.6 Useful-to-detrimental ratio’s

This method of speech intelligibility measures was first introduced by (Lochner and Burger, 1958), “which essentially predicts early to late sound ratio with background sound energy combined to the late arriving sound”. “This method predicts speech intelligibility scores based on useful energy calculated from a weighted sum of sound energy arriving in the first 95 msec, by using the equating derived by Lochner and Burger”:

$$C_{[95]} = 10 \log \left[\frac{f_{0.0}^{0.095} \propto p^2(t)dt}{f_{0.095}^{\infty} p^2(t)dt} \right] dB \cdots\cdots\cdots\cdots\cdots\cdots (v)$$

Where (**a**) is known as “the fraction of energy of each individual reflection integrated into the useful energy sum, which can be approximately calculated by the equation derived by Bradley”:

$$\propto = [(2.3 - 0.6\mathrm{ra}^{0.7}) + (0.0248\mathrm{t} - 0.00177\mathrm{ra}^{1.35})\mathrm{t}] \cdots\cdots\cdots\cdots\cdots \text{(vi)}$$

Where *(ra)* is the relative amplitude of the reflection and (t) its relative delay.

Suppose (SL and BL) are the steady-state long-term (rms) speech and background level and the ($E_{SL} - E_{BL}$) are the related total speech and background energies, then the useful energy can be estimated using the equation derived by Bradley (Bradley, 1986):

$$\begin{aligned}&\mathrm{Useful} = [\mathrm{E_e}/(\mathrm{E_e} + \mathrm{E_1})] \cdot \mathrm{E_{SL}}\\ &= [\mathrm{C_{te}}/(\mathrm{C_{te}} + 1)] \cdot \mathrm{E_{SL}} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{(vii)}\end{aligned}$$

Where E_e and E_1 are the relative and late energy sums from uncelebrated pulse recordings and C_{te} is the linear early/late ratio with an early time limit te.
Therefore, Bradley derived the detrimental equation as below:

$$\mathrm{Detrimental} = [1/(\mathrm{C_{te}} + 1)] \cdot \mathrm{E_{SL}} - \mathrm{E_{BL}} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{(viii)}$$

When equation (vii) is divided by(vii), an expression for useful/detrimental ratio is obtained for any early sound limit(te), which is given by:

$$\mathrm{U_{te}} = \mathrm{C_{te}}/[1 + (\mathrm{C_{te}} + 1) \cdot \mathrm{E_{BL}}/\mathrm{E_{SL}}] \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{(ix)}$$

Furthermore, useful/detrimental sound ratio can be calculated from the corresponding early-to-late ratio C_{te} and the ratio of background noise to speech energies. Bradley also "argued that other early-to-late ratio can be calculated, for example U_{80} derived fromC_{80}, which he assumed to be safe and more reliable predictor of intelligibly" (Bradley, 1986).

Bradley also "derived the following relationship from the best-fit third order polynomial for each data of U_{80} and U_{95} from the best-fit curve for predicting speech intelligibility which is given by the following equation":

$$\mathrm{SI} = 1.219 \cdot \mathrm{U}_{80} - 0.02466 \cdot \mathrm{U}_{80}^{2} + 0.00295 \cdot \mathrm{U}_{80}^{3} + 95.6 \ldots \ldots \ldots \text{(x)}$$

$$\mathrm{SI} = 0.7348 \cdot \mathrm{U}_{95} - 0.09943 \cdot \mathrm{U}_{95}^{2} - 0.0005457 \cdot \mathrm{U}_{95}^{2} + 1.97. \ldots \text{(xi)}$$

Chapter 3

RESEARCH METHODOLOGY

3.1 Introduction

The purpose of this section is to consider the research design which deals with the ways information were gathered to accomplish the research aims and objectives. In this study both qualitative and quantitative research method were used to identify the acoustic problems – its sources, effects, and possible control, hence the research instrument that was adopted are measurement and scaling techniques, personal observation and desk review. The research instruments adopted in this research include the following:

3.2 Measurement and Scaling Techniques

A set of instruments was used to educe relevant information or data on the particular issues or problems (i.e. Noise problems) and was later analyzed to provide a suitable and appropriate solution to the problems and the issues at hand. Among this instrument that are used to predict the sound or speech intelligibility level in the hall are the, Sound level meter, microphone and DIRAC program aided with a standard window PC (computer) to calculate the EDT, INR, SNR, C80, D50,H, BR(RT), RT and RAST, from 20 different points in the Hall.

Microsoft excel software was also used to construct tables. Averages, minimum and maximum values of sound levels were considered in this research study.

3.3 Personal Observation

Aerial photographs were taken on the area in question (LaLa Mustafa Pasa Sport Complex- Eastern Mediterranean University, Gazimağus) so as to have a first hand and pictorial information on the issues or problems. Direct observations was also made, considering noise sources from inside and outside the building, building orientation, the sitting arrangement, and dimensions of the entire Hall was recorded to support this research.

3.4 Desk Review of Related Literature

Relevant textbook and publications including websites (internet) was used to support the data and information that are needed.

Chapter 4

DATA PRESENTATION, ANALYSIS AND DISCUSSION

4.1 Introduction

The purpose of this chapter is for data presentation, analysis and interpretation of the data collected from the research source-LaLa Mustafa Pasa Sport Complex. Tables were used to analyse the data collected and they were arranged with respect to statement below, which include the description of the Hall under survey and personal data. A survey was carried out in the hall to reveal the acoustical defects affecting the space, as well as direct observation considering intrusive noise sources into the space, building orientations, the sitting arrangement, dimensions of the space and the building as a whole. In addition, photographic records of both the interior and exterior, plans and sections for correlation with the survey were made as it affects the acoustical suitability of the hall, as shown in figures 4.1, 4.2, 4.3, 4.4 and 4.5 respectively. Measurements also were taken from various points in the hall to identify the speech intelligibility and reverberation (Echo) problems of the entire space, as indicated in figure 4.6.

4.2 LaLa Mustafa Pasa Sport Complex specification/description

From table 4.1, it could be seen that LaLa Mustafa Pasa Sport Complex is located at Eastern Mediterranean University (E.M.U), Gazimağus in Turkish Republic of Northern Cyprus. The hall interior space is about 3172 m^2 in area and approximately 45846 m^3 in volume with 3,500 seats. The interior space which is meant for sport, speeches and other activities has a reverberation time (RT) of about 4.5 [s] and rapid speech transmission index (RASTI) of about 0.34 [−] with total hall length of about 221 m, true area/seat of 0.25m^2, true seating area of 875 m^2, volume per seat of 0.175m^3 and stage area of 76.2 m^2.

Table 4.1: LaLa Mustafa Pasha Hall specifications

S/N	Specification	Approximate Value
1.	Name of hall	LaLa Mustafa Pasa Sport Complex
2.	Location	E.M.U, Gazimagusa [T.R.N.C]
3.	Area	3172 m^2
4.	Volume	45846 m^3
5.	Total length (perimeter)	221 m^2
6.	Number of seats	3500 seats
7.	Mid frequency [500-1000Hz] RT [s]	4.9-4.4 [s]
8.	Mid frequency [500-1000Hz] EDT [s]	4.7-4.1 [s]
9.	RT[s]	4.5
10	RASTI [-]	0.34 [-]
11.	Stage area	76.2 m^2
12.	Volume per seat	0.175 m^3
13.	True seating area	875 m^2
14.	True area/seat	0.25 m^2

[Source: Field survey, 2011]

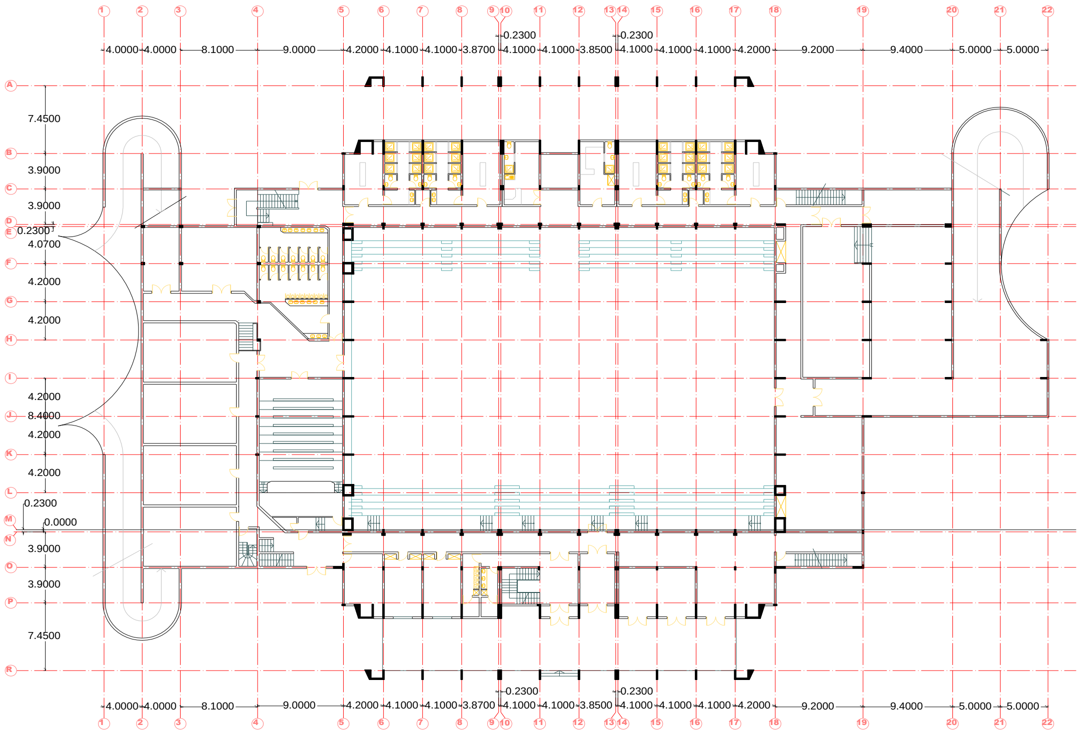


Figure. 4.1: LaLa Mustafa Pasa ground floor plan [Researcher’s field study, 2011]

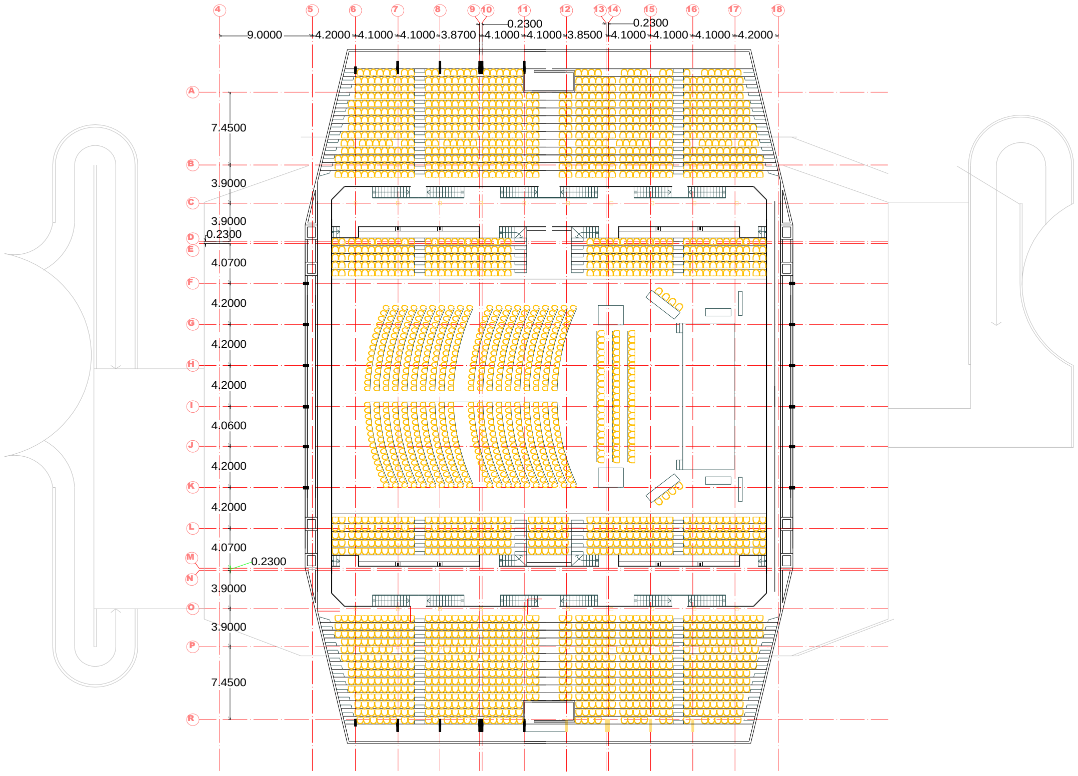


Figure. 4.2: LaLa Mustafa Pasa first floor plan with sitting arrangement [Field study, 2011]

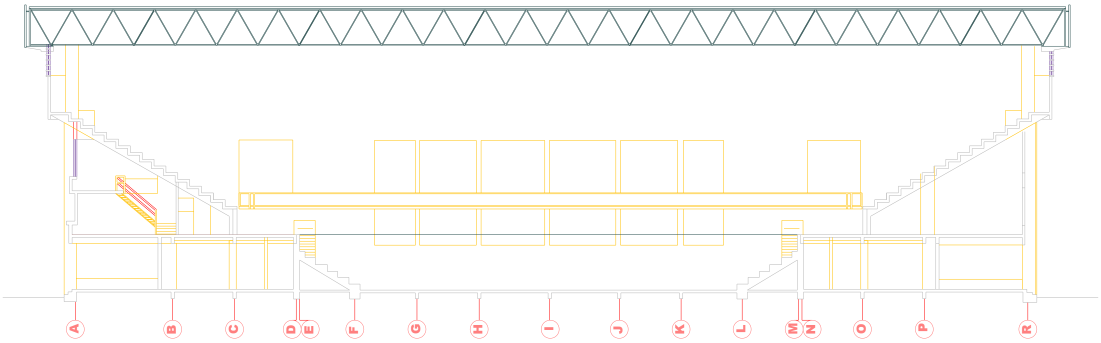


Figure. 4.3: LaLa Mustafa Pasa long section [Source: Field study, 2011]

Figure. 4.4: A view through the sitting arrangement of LaLa Mustafa Pasa Hall in the 2010 Fall graduation ceremony [Field study, 2011]

Figure. 4.5: Exterior view of LaLa Mustafa Pasa Sport Complex [Field study, 2011]

4.3 Results and analysis of research questions one and two

Question 1-What are the ways to identify possible existing acoustic problems?

Question 2-What appropriate method to be used to analyze the problems identified?

The aim of these questions is to find out the possible existing acoustic problems in LaLa Mustafa Pasa sport complex and its environs. This was identified by measurements from various points or locations within the hall, as shown in figure 4.6, with the aid of a sound level mater attached to microphone and DIRAC program, which automatically captured and calculated the EDT[s], T10, T20[s], T30[s], RT[s], INR [dB], SNR [dB], C80 [dB] D50 [-] and RASTI [-] of each point in 10 octave bands (from 31.5Hz to 16000KHz). Below are the hall first measurement's results from 20 points within the hall, Pt1, Pt2, Pt3, Pt4, Pt5………………, and Pt20 respectively, when the hall is not occupied.

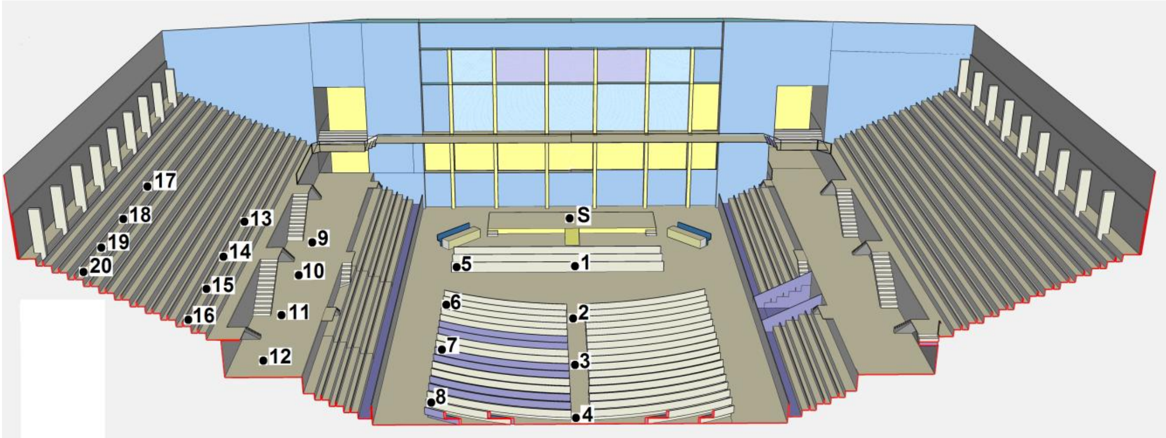


Figure. 4.6: Interior perspective of the hall showing the points of measurements [Field study, 2011]

4.3.1 Measurements average result values for EDT[s], RT[s], INR[dB], SNR[dB], C80[dB] D50[-] and H[dB] from pt1 to pt20

Table 4.2 below shows the summarised average measurement result values for EDT[s], RT[s], INR[dB], SNR[dB], C80[dB] D50[-] and H[dB] from 20 points within the hall between (125 Hz to 4000KHz) octave bands frequencies. The table also shows the optimum values for EDT EDT[s], RT[s], C80 [dB] and D50[-] for a typical multipurpose building/Hall.

Table 4.2: Average measurement result values for EDT[s], RT[s], INR [dB], SNR [dB], C80 [dB] D50 [-] and H[dB] from point 1to 20.

Frequency Hz	**125**	**250**	**500**	**1000**	**2000**	**4000**	**Optimum Range Values**
	Low Frequency		**Mid Frequency**		**High Frequency**		
EDT[S]	**4,1**	**5,0**	**4,7**	**4,1**	**4,2**	**2,9**	**1,4-1,9**
RT[S]	**4,2**	**4,6**	**4,9**	**4,4**	**4,3**	**3,3**	**1,6-1,8**
INR[dB]	**23,15**	**24,9**	**25**	**26**	**26,7**	**23,5**	**-**
SNR[dB]	**11,9**	**12,8**	**12,9**	**13,6**	**11,4**	**7,8**	**+15**
C80 [-]	**-3,3**	**-3,6**	**-2,9**	**-2,8**	**-3,3**	**- 1,8**	**-2-+2**
D50[-]	**0,3**	**0,2**	**0,2**	**0,3**	**0,2**	**0,3**	**>0.20**
H[dB]	**6,4**	**7,0**	**6,8**	**5,9**	**6,3**	**4,8**	**-**

[Source: Field study, 2011]

From the analysis as shown in table 4.2, it was deduced that the mid reverberation time [RT] average from 500-1000Hz is 4.9-4.4s and mid early decay time [EDT] of the same frequencies is 4.7- 4.1s, exceeds the optimum require values for general multipurpose use. This indicated that the Hall suffers from sound distribution problem and also shows that the surfaces of the hall is not at most times results to early reflections on users of the Hall. However the measurements are for unoccupied Hall.

For multi-purpose use the optimum range for clarity is given as -2 to +2 dB (Barron, 20090). It was equally observed that the speech clarity of this particular Hall at mid frequencies (i.e. 500-1000Hz is -2.9 to -2.8) exceeds the optimum range value for multipurpose use, which shows that this have an effect on the speech intelligibility of the Hall as a Whole. Below is the graphical representation of the average values for the EDT[s] and RT[s].

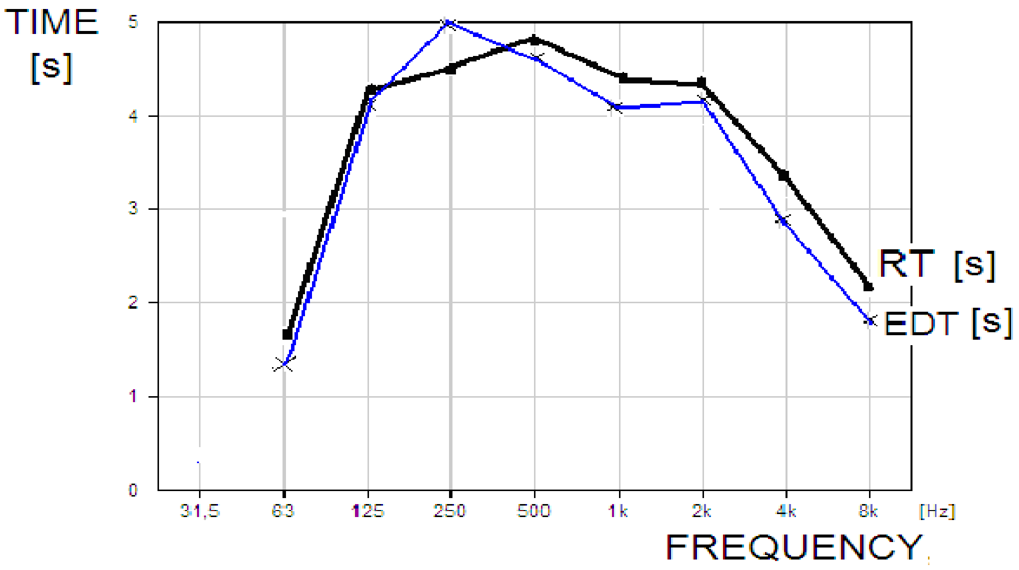
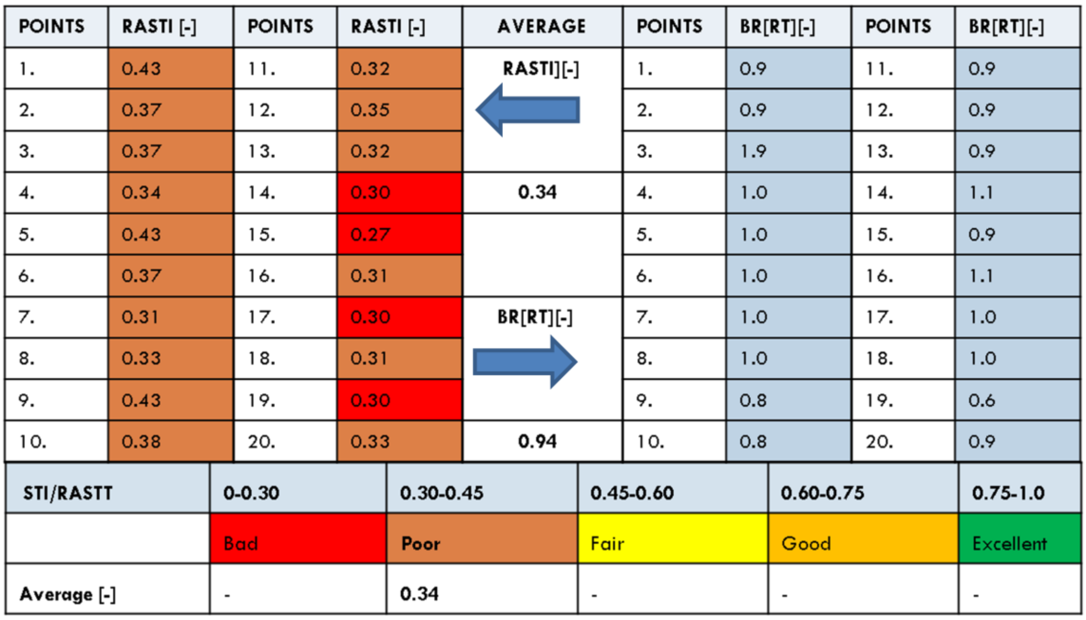


Figure. 4.7: Graphical representation of the EDT[s] and RT[s] [Field study, 2011]

Figure 4.7 shows the graphical analysis of the average EDT and RT values. It was observed that the RT values are greater than the EDT. However, at mid frequency the values are much closer. The gap difference between the EDT and RT shows that the sound distribution in the entire Hall is bad, which implies that the reverberation time of the Hall is high and is above optimum range. Whereas the values of the EDT with average minimum value of 1.4s and maximum of 5.0, indicates that the surfaces of the hall is not encouraging and at most times results to early reflections on users of the Hall, since the EDT greatly depend on the room geometry and distinctness of the absorptive and the reflective surfaces in the Hall.

4.3.2 Measurements result values for BR (RT) [-] and RASTI [-] from 20 points within the hall.

Table 4.3 below shows all the measurement result values for BR (RT) [-] and RASTI [-] from pt1 to 20 within the hall and the BR (RT) [-] and RASTI [-].



POINTS	RASTI [-]	POINTS	RASTI [-]	AVERAGE	POINTS	BR[RT][-]	POINTS	BR[RT][-]
1.	0.43	11.	0.32	RASTI][-]	1.	0.9	11.	0.9
2.	0.37	12.	0.35	⬅	2.	0.9	12.	0.9
3.	0.37	13.	0.32		3.	1.9	13.	0.9
4.	0.34	14.	0.30	0.34	4.	1.0	14.	1.1
5.	0.43	15.	0.27		5.	1.0	15.	0.9
6.	0.37	16.	0.31		6.	1.0	16.	1.1
7.	0.31	17.	0.30	BR[RT][-]	7.	1.0	17.	1.0
8.	0.33	18.	0.31	➡	8.	1.0	18.	1.0
9.	0.43	19.	0.30		9.	0.8	19.	0.6
10.	0.38	20.	0.33	0.94	10.	0.8	20.	0.9

STI/RASTT	0-0.30	0.30-0.45	0.45-0.60	0.60-0.75	0.75-1.0
	Bad	Poor	Fair	Good	Excellent
Average [-]	-	0.34	-	-	-

[Source: Field survey, 2011]

Table 4.3, gives the summary results for the **RASTI's and BR [RT]'s** gathered from the field study measurements. To determine the speech intelligibility, the RASTI was measure at different points of the Hall as indicated in the table 4.3, using sound level meter, microphone and DIRAC program. Taking the measurements from Pt1-Pt13, Pt16 and Pt18 it was deduced that the speech intelligibility on these points were found to be poor, while Pt14, Pt15, and Pt17 were found to be bad. From the results obtained in the measurements it could be justified from the **RASTI** average **0.34 [-]**, that the speech intelligibility condition of the total hall was generally poor. It was also discovered that the average **BR (RT)** was **0.94 [-]**, which implies that the entire hall is suffering from background noise and reverberation problem.

4.4 Summary of the results gathered from the field survey for echo measurements using ray tracing.

Figures 4.8 and 4.16 are plans showing the centre setting arrangement and how impulse sound or echo travels in the Hall, with the indication of the listener's sitting positions at (a1, b1, c1, d1, e1, f1and g1) and (a3, b3, c3, d3, e3, f3and g3). The position of the speaker is represented by capital letter (S), and the green arrows denotes the first sound path the listener (L) perceives as direct sound, which is then accompanied by series of early reflection ray paths denoted by red arrows as indicated in figures 4.9 to 4.15 and 4.16.

(a) In figures 4.9 to 4.15, sound is emitted from the source or speaker (S) to strike the ceiling at (T), afterwards reflects to the wall (U), in turn to the listener at (L), and then back to the original starting point of travel the speaker at (S).

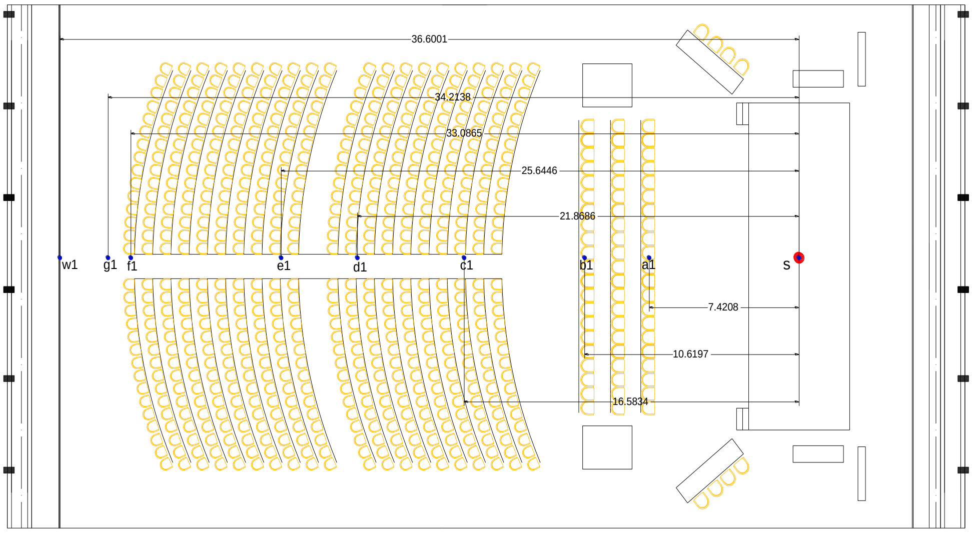


Figure. 4.8: Plan A-A [Field study, 2011]

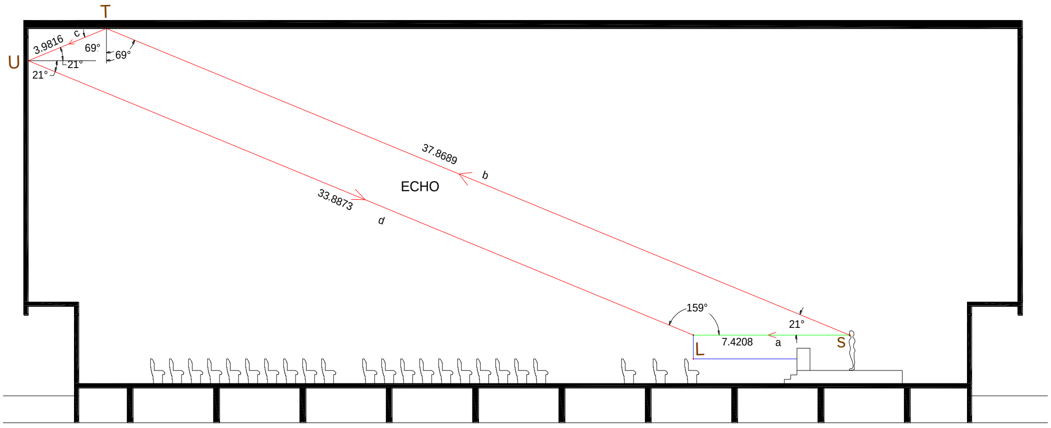


Figure. 4.9: Section AA (Point ***a*1** from Plan A-A) [Field study, 2011]

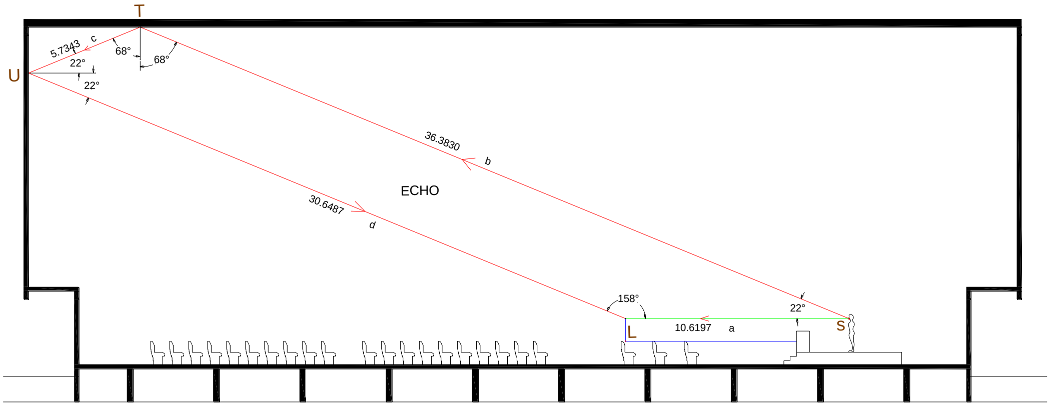


Figure. 4.10: Section AB (Point ***b*1** from Plan A-A) [Field study, 2011]

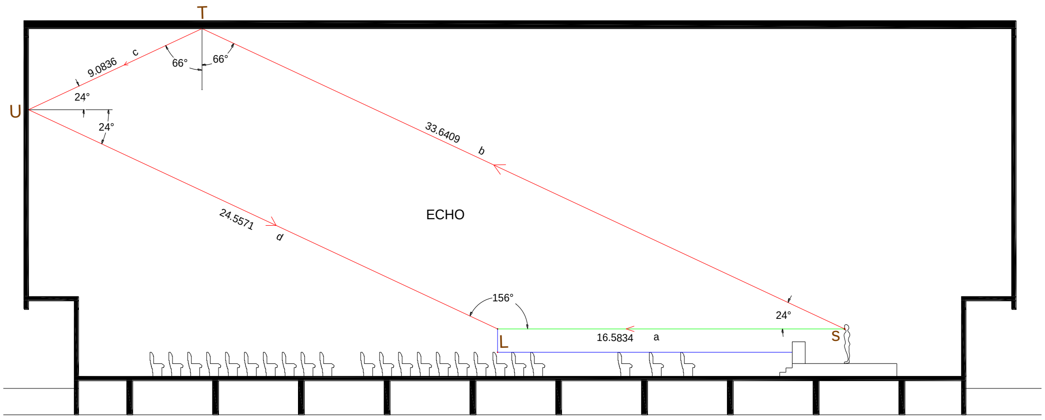


Figure. 4.11: Section AC (Point ***c*1** from Plan A-A) [Field study, 2011]

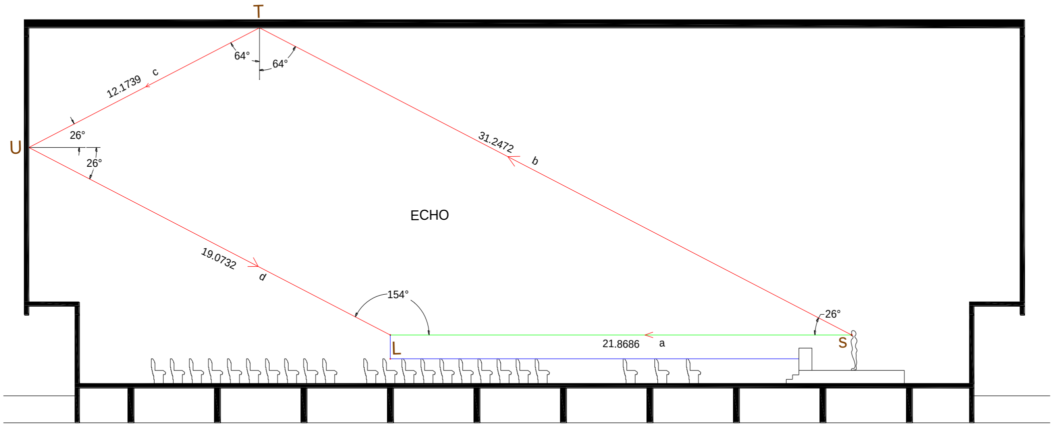


Figure. 4.12: Section AD (Point ***d*1** from Plan A-A) [Field study, 2011]

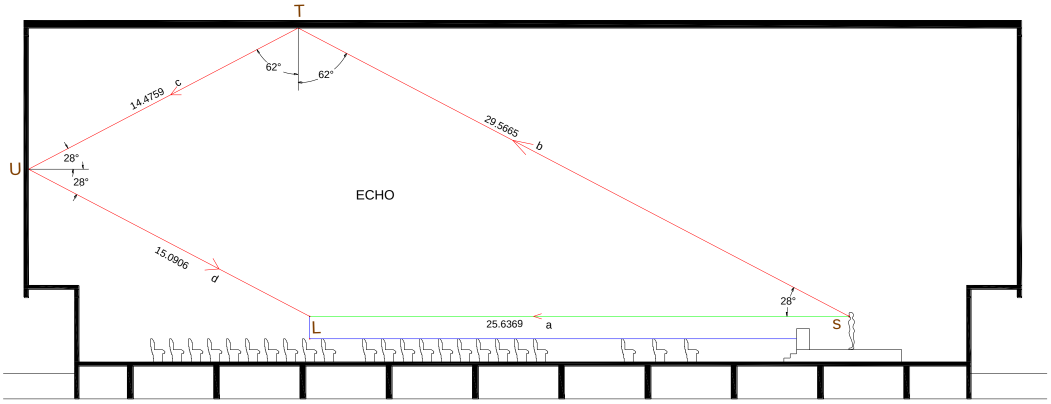


Figure. 4.13: Section AE (Point ***e*1** from Plan A-A) [Field study, 2011]

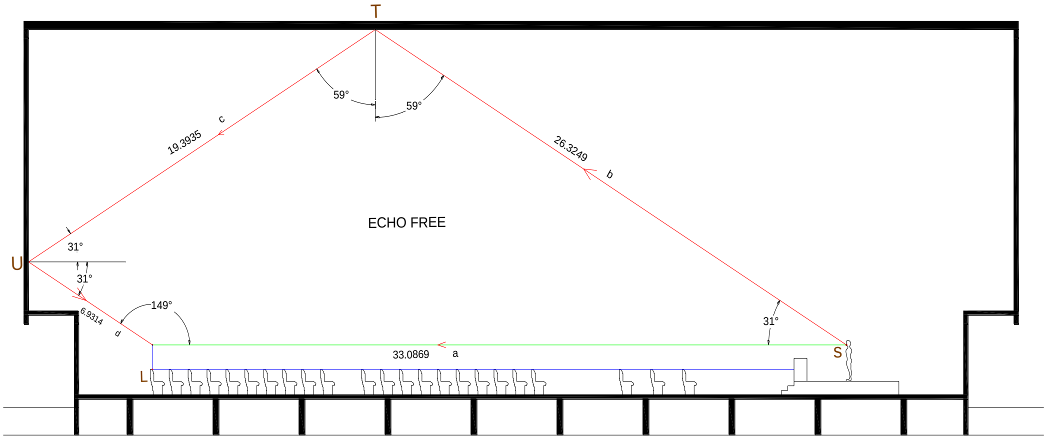


Figure. 4.14: Section AF (Point $\boldsymbol{f1}$ from Plan A-A) [Field study, 2011]

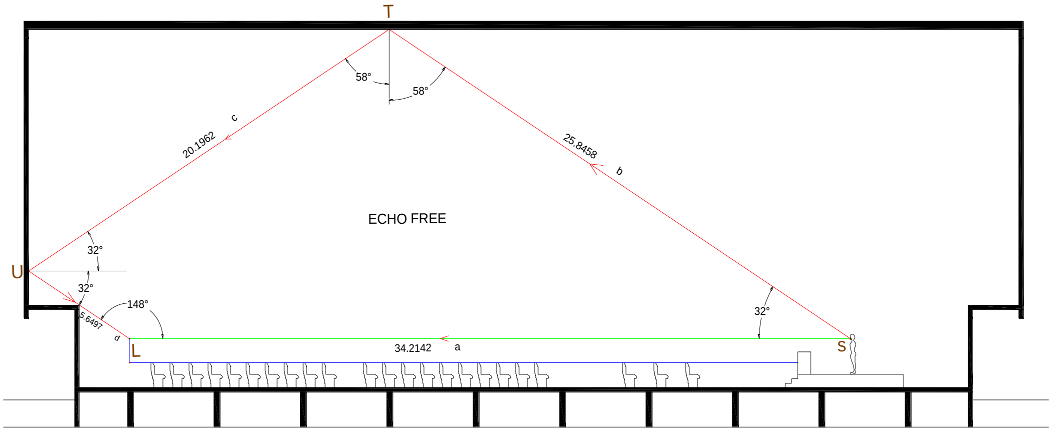


Figure. 4.15: Section AG (Point $\boldsymbol{g1}$ from Plan A-A) [Field study, 2011]

Table. 4.4: Summary echo results from section AA, AB, AC, AD, AE, AF, and AG

Points from section AA, AB, AC, AD, AE, AF and AG [Plan A-A]					**Echo Regions**	**Echo Free Regions**
Sections	ST = b	TU = c	LU = d	LS = a	$[\mathrm{ST}+\mathrm{TU}+\mathrm{LU}] - \mathrm{LS} > 20m$	$[\mathrm{ST}+\mathrm{TU}+\mathrm{LU}] - \mathrm{LS} < 20m$
Section AA	37.8689m	3.9816m	33.8873m	7.4208m	**68.3m (0.20s)**	
Section AB	36.3830m	5.7343m	30.6487m	10.6197m	**62.1m (0.18s)**	
Section AC	33.6409m	9.0836m	24.5571m	16.5834m	**50.7m (0.15s)**	
Section AD	31.2472m	12.1739m	19.0732m	21.8686m	**40.6 m (0.12s)**	
Section AE	29.5665m	14.4759m	15.0906m	25.6369m	**33.5m (0.10s)**	
Section AF	26.3249m	19.3935m	6.9314m	33.0869m		**19.6m (0.06s)**
Section AG	25.8458m	20.1962m	5.6497m	34.2142m		**17.5m (0.05s)**

[Source: Field survey 2011]

Table 4.4 gives the summary of echo results from section AA, AB, AC, AD, AE, AF and AG (i.e. figure 4.9-4.15) of plan A-A (figure 4.8).

Considering a sound emitted from a speaker at (S), in turn hits the ceiling at (T), then reflect to the wall at (U), and reflect back to the source S again, as illustrated in figure 4.9 to 4.15, it was discovered that a listener at point a1 in the hall would experience too much echo as shown in figures 4.8 and 4.9 than a listener at point c1 as shown in figure 4.11. At points f and g1 in figures 4.14 and 4.15, there were found to be echo free, in which the listener will not experience any echo at these points but the speaker need to strain his voice for the listener at point f1 and g1 to hear him or her spoken word. In this case the listeners only depend on the speaker’s mouth movement to detect or understand the spoken word or message. From all indications, a listener at point (b1, d1, and e1), as shown in (figure 4.10, 4.12 and 4.1) also experiences echo but not as much as a1. The farther the listener from the speaker (S) the less the echo and the nearer the listener (L) the greater the echo.

(b) In figure 4.16, sound is emitted from the source or speaker (S) to hit the first side wall of the Hall at T, U, V, W, X, Y, and Z as illustrated in figure 4.16, afterwards reflects to the listener at points a3, b3, c3, d3, e3, f3 and g3, and then back to original starting point of travel the speaker at (s).

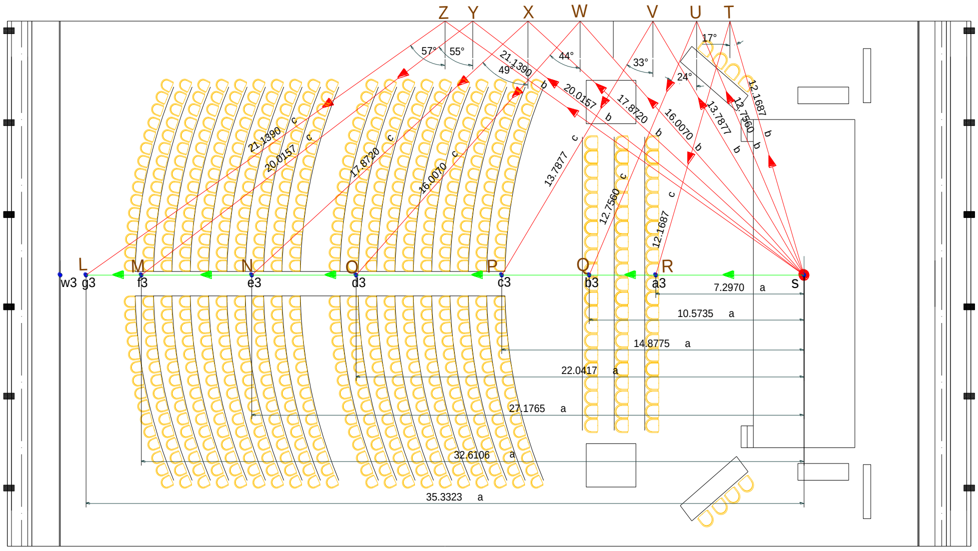


Figure. 4.16: Plan B-B [Field study, 2011]

Table. 4.5: Summary echo results for first side wall from [Plan B-B]

Listener's points a3, b3, c3, d3, e3, f3 and g3 [Plan B-B]				**Echo Regions**	**Echo Free Regions**
points	b	c	a	[b + c] − a > $20\,m$	[b + c] − a < $20m$
a3	12.1687m	12.1687m	7.2970m	-	**17.0m (0.05s)**
b3	12.7560m	12.7560m	10.5735m	-	**14.9m (0.04s)**
c3	13.7875m	13.7875m	14.8775m	-	**12.7m (0.04s)**
d3	16.0070m	16.0070m	20.0417m	-	**12.0m (0.04s)**
e3	17.8720m	17.8720m	27.1765m	-	**8.60m (0.03s)**
f3	20.0147m	20.0147m	32.6106m	-	**7.40m (0.02s)**
g3	21.1390m	21.1390m	35.3323m	-	**6.90m (0.02s)**
Average					**11.4m (0.03s)**

[Source: Field survey 2011]

Table 4.5 gives the summary of the first side wall echo results of plan B-B of the Hall, as shown in figure 4.16. In figure 4.16, T, U, V, W, X, Y, and Z denotes the first side walls of the hall and a3, b3, c3, d3, e3, f3 and g3 the listener's position. The arrows on red are the early reflections, while the one on green represents the direct sound that is first heard by the listener from the speaker at S, as in figure 4.16. From the field survey it was observed that sound hitting the first side walls of the hall from the speaker at S, which average is 11.4m (0.03s), will not send back (i.e. there will be no echo) echo to the listener, as shown in table 4.13.

In the nutshell, results taken from 20 different points within the hall to identify the speech intelligibility defect and background noise disclosed that the average **RASTI** and **(RT)** are **0.34** and **4.5** respectively, which demonstrated that the hall is having speech intelligibility, reverberation, echo and background noise problems.

Moreover, results gathered from the ray tracing diagrams showing how sounds travels in the hall proved beyond reasonable doubt that there is severe echo at the front seat, mild towards the back seats and echo free at the back seats as shown in figures 4.13 and 4.14 at point f1 and g1 of plan A-A illustrated in figure 4.12. However, it was discovered that there will be echo free when sound is emitted from the speaker to hit the first side walls of the Hall at T, U, V, W, X, Y, and Z, as in figure 4.16 1 and table 4.13. It was also inferred that speech strain is an acute problem for the users of the Hall. The speaker at most times need to speak for a long period of time at an elevated voice for the listeners or audience to hear his or her spoken messages or words, the listener only rely on the mouth movement to understand the speaker, especially during graduation ceremony.

Furthermore, in some cases, the speaker experiences a higher incidence of voice problems than the general audience or listeners.

Chapter 5

RECOMMENDATION AND CONCLUSION

5.1 Recommendations for Possible Noise Control Measures in LaLa Mustafa Pasa Sport Complex

The provision of adequate and pleasant listening space in LaLa Mustafa Pasa Sports Complex is very important for the users in general, since uncoordinated noisy environment can lead to several health hazards. Against this background the study proffers the following recommendations.

1. Application of natural terrain such as tress and artificial barriers such as screen to provide additional shielding and prevent traffic noise from intruding into the hall from the outside should be introduced.
2. Hanging baffles such as ANC-600P premium ceiling baffles should be hanged freely from the Hall trusses to interrupt the path of noise and reduce the amount of sound reverberation. It has a noise rating criteria (NRC) of 1.15 per 4' x 2' (0.10m-0.05m) Baffle and has a Class A fire rating per ASTM E-84. It also has lowers center frequency of maximum absorption to 125 Hz (0.46) and mid to high frequency absorption is typically 500Hz (1.07) to 2000Hz (1.01). This type of baffles is capable of withstanding abuse from basketballs, volleyballs and the like. 24" - 35" (0.61m to 0.82m) apart over the entire reverberant hall can result in approximately 4 - 12 decibel reduction in general noise.

3. Wall diffuser such as double duty diffuser^{TM} (polycylindrical fabric covered), should be placed on side and real wall to conserve or act to scatter high frequency sound and trap bass in any location of the hall. The bass absorption vary with size. A 2’ x 4’ (0.05m-0.10m) unit is recommended because it has maximum absorption at approximately 125 Hz. Increasing size to 4’ x 8’ (0.10m x 0.20m) lowers center frequency of maximum absorption to 63 Hz. Mid to high frequency absorption is typically 0.10 to 0.25 and has a noise rating criteria (NRC) 0.10. This type of diffuser is also capable of increasing absorption and prevents resonance.
4. Wall panel such as Ripstop nylon material should be used on side and rear walls; because such panels covered with Ripstop nylon offers an extremely durable baffle that can withstand abuse from basketballs and volleyballs. These fiberglass filled wall panel is excellent for acoustical treatment in large open rooms and work well to reduce reverberation and increase speech intelligibility.
5. Acoustic carpet underlay such as silentstep or impact barrier® LD carpet underlayment should be install on the floors of the hall (i.e. the walk way in between the seats and large corridor) to maximise noise by providing superior airborne noise transmission loss and excellent impact noise. These products are extremely effective in reducing impact sound from footfall and very effective in reducing airborne sound transmission and add comfort to your carpeted floor. These products are also engineered for low pile carpets and qualify as a Class II heavy traffic commercial grade products. However, maintenance and replacement cost should be considered.
6. Cracks and openings around conduits, pipes, or ducts should be sealed by using ANC-WB42 Loaded Vinyl, Composite Noise Wrap Barrier. This composite

prevent noise that transmits through the walls of the pipe or duct as air or other contents move through it. In addition it also increases the sound absorption in the cavity and provides sound absorption and thermal insulation around the pipe or ductwork. Among other products, ANC-WB4 loaded vinyl has a smoke density index of 19.5, flame spread index of 12.5 and has a class A flammability rating per ASTM E-84 which makes the product a good fire resistance. It can also withstand temperature of -10° to +180° F and which makes it a good insulator. This product is also recommended because of noise rating criteria (NRC) of 30 with lower center frequency of 19 (125Hz) and mid to high frequency abortion of 23(500Hz) and 23(2000Hz) respectively.

7. Quality electronic sound reinforcement system should be used to reduce sound that will mask speech intelligibility. Without good acoustic reinforcement from surfaces, sound may dominate the room and might lead to unnatural sound.
8. Replacement of existing windows with insulated glass such as double glazing of 1/4” air space cavity with STC rating of 51 should be used, however the larger the air cavity the better the STC rating, or acoustical lovers to reduce traffic noise (air-born sound) from intruding into the hall from the exterior (outside). This double glazing reduces a 60 dB outside traffic noise level to 40 dB within the hall and it also improves the thermal performance of the hall.

5.2 Conclusion

In conclusion, a multipurpose space should be able to handle a wide range of functions. It should be designed with several lighting systems, have acoustically treated walls and ceilings, and be technologically integrated and easily maintained. A good multipurpose space should be able to satisfy the needs of its assigned functions at reasonably high levels of performance. Whether they are used for multimedia presentations, stage and musical productions, physical education, or sport activities, acoustic issues need to be addressed in the design phase or stage to minimize some of the hazards in the multipurpose spaces/ auditoria and other related buildings in general. They must also be improved upon to ensure pleasant environment for the occupants after completion. It was clearly observed from the study that the major surfaces in an auditorium have important implications on the acoustical quality of a place. As a result acoustic balance maintains desired characteristics of speech intelligibility, reverberation time, and echo to mention but three factors only.

In this research, DIRAC computer program was used for the assessment of the acoustical defects of the unoccupied Hall. The results from the research for [RT] and [EDT] show that there is excessive reverberation time and early decay time throughout the Hall, since the optimum range reverberation time and early decay time for multipurpose Halls should not exceed between 1.6 to 1.8s and 1.4 to 1.9s respectively. The research results also show that the bass balance which is the ratio of mid frequency [RT] to high frequency [RT] falls above the optimum range.

It was also confirmed that clarity was undermined by excessive reverberance sound, which in turn affects speech in the entire hall. The speech intelligibility of this hall was found to be poor, which disclosed that the hall is having severe speech intelligibility problem. Another aspect is the sound level distribution from the echo ray tracing, which shows that the hall has no reflectors and absorbing materials to reflect and absorb sound sufficiently through the hall and as a result led to the formation of echo, longer reverberation and poor quality of sound distribution throughout the hall. Moreover, in this case the direct sound becomes inadequate at the middle and back seats locations of the hall.

Results gathered from the ray tracing also show that there is severe echo at the front, middle and echo free at the last back seats. However, speech strain is an acute problem for the users of the hall. The speaker at most times need to speak for a long period of time at an elevated voice for the listeners or audience to hear his or her spoken words, the listener only depends on the mouth movement to understand the speaker. Furthermore, in some cases, the speaker experiences a higher incidence of voice problems than the general audience or listeners.

Consequently, in order to avoid acoustical defects, precautions has to be taken from the design stage as earlier mentioned, since eradicating acoustic defects completely in large buildings is almost inevitable. However, the acoustics of LaLa Mustafa Pasha Sport Complex should be taken care of by implementing the above recommendation to mitigate or attenuate the noise defects to the minimal, since noise can be controlled by modifying the source, the path and the receiver, using sound absorbing materials, sound barriers or deflectors, acoustical linings, and other sound control materials.

5.2.1 Suggestions for further research

(i) Further research could be made to ameliorate the acoustical stability of this hall by using acoustic model testing to identify the diffuse and specula reflections and will address many of the drawbacks of previously reported models, level of speech intelligibility and other factors through a technique known as "Auralisation". This will be finally achieved by the use of personal computer software called "ODEAN" software to predict the acoustical defects of the hall. This program also improves the room acoustics of existing buildings or halls.

(ii) Apart from the economical ways and materials mentioned in this research for mitigating sound in LaLa Mustafa Hall of EMU, North Cyprus, further study could also be research upon on the newest best durable sound absorbing materials to be used to control sound in the Hall. Moreover, the most economic aspect of these suggestions should be studied upon as well.

(iii) Further research could also be done on the hall to determine occupied reverberation time [RT] for correlation with the unoccupied reverberation time [RT] result measured in this research.

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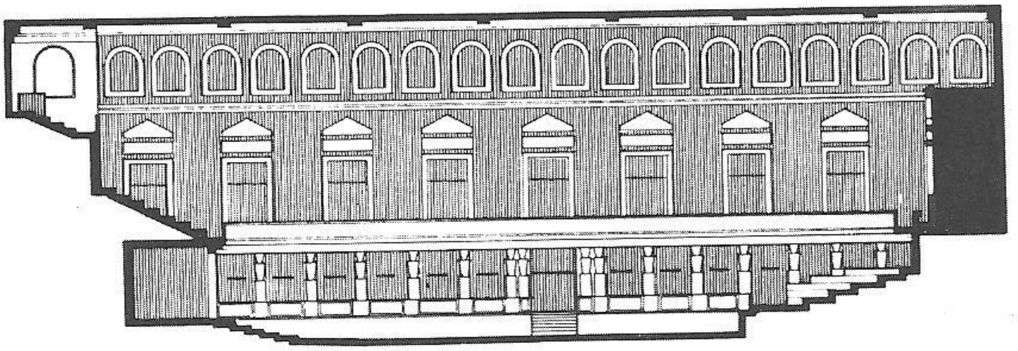
APPENDICES

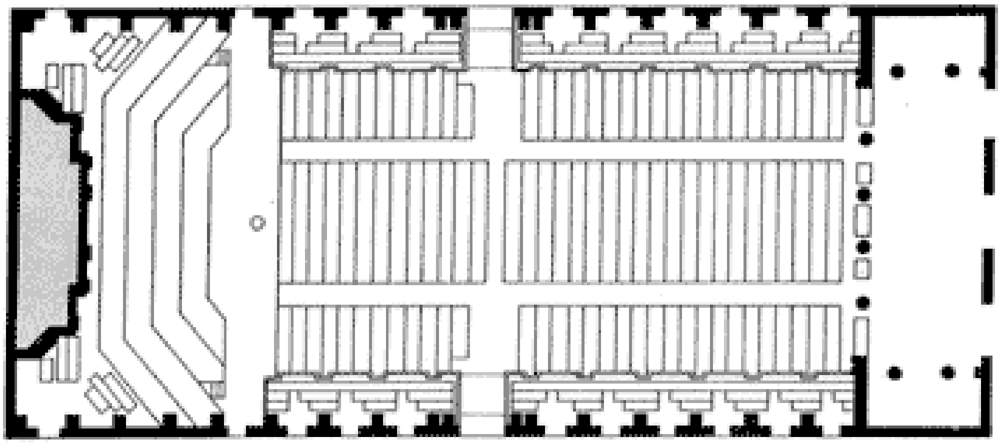
Appendix A: Plate 1

Grosser Musikvereinssaal, Vienna

Grosser Musikvereinssaal (Interior) [Beranek, 2004, Long, 2006]



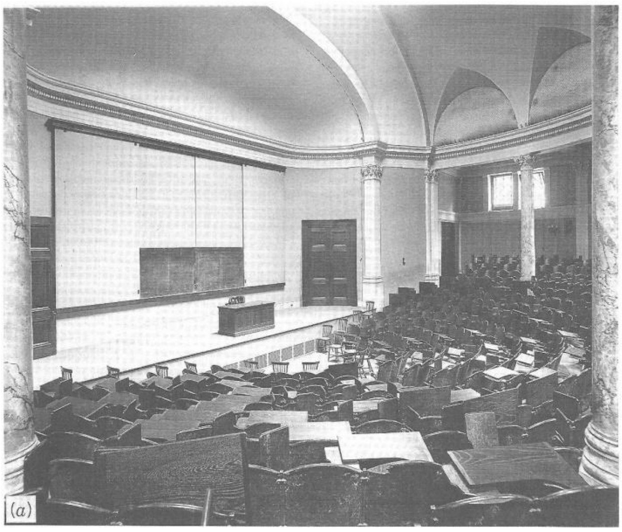
Grosser Musikvereinssaal, Vienna (Long section) [Barron, 2009]



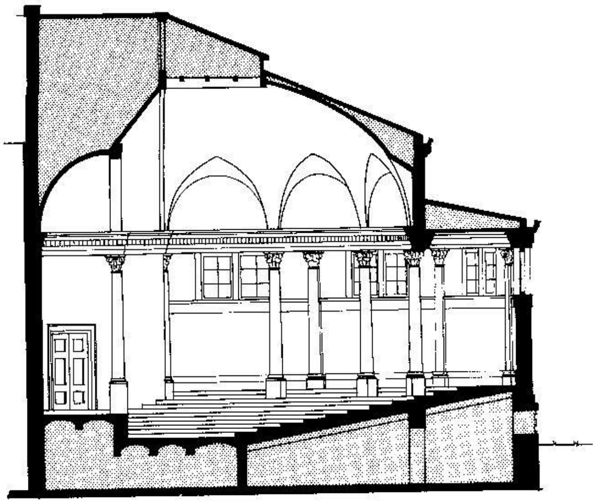
Grosser Musikvereinssaal, Vienna (Plan) [Beranek, 2004, Long, 2006]

Appendix B: Plate 2

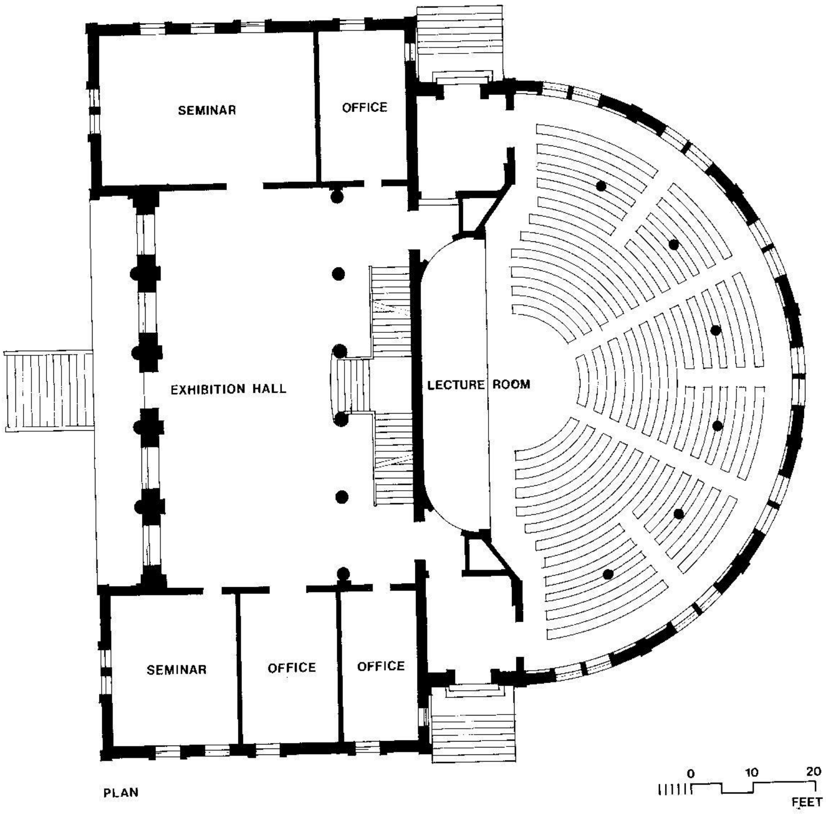
Fogg Art Museum, Cambridge



Fogg art museum Lecture hall (Interior)



Fogg art museum (Section)

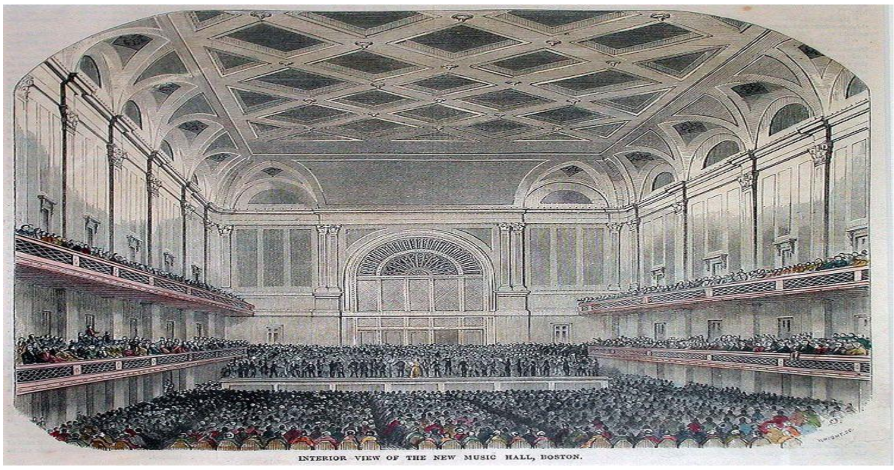


Fogg art museum (Plan)

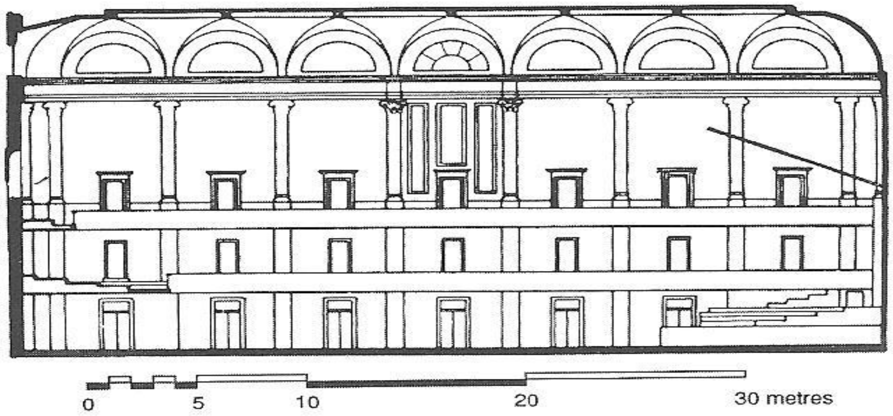
[**Source**: Cavanaugh and Wilkes, 1999]

Appendix C: Plate 3

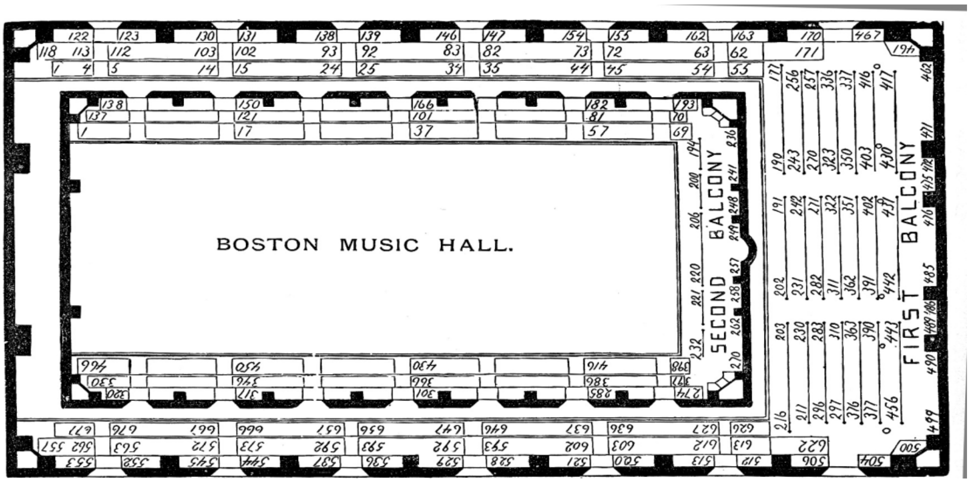
Boston music hall, Massachusetts



Boston music hall (Interior) [Long, 2006]



Boston music hall (Section) [Barron, 2009]

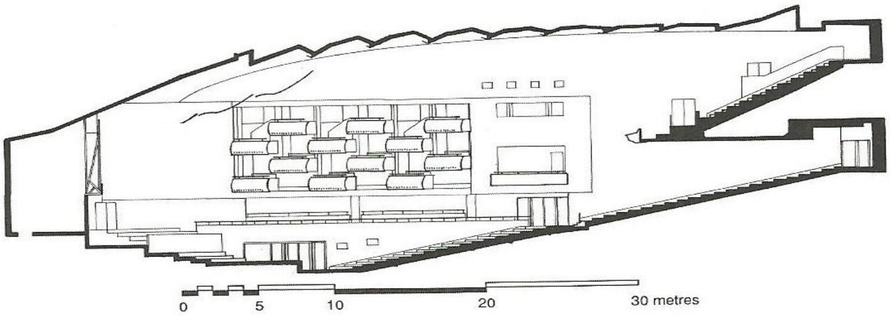


Boston music hall (Plan) [Long, 2006]

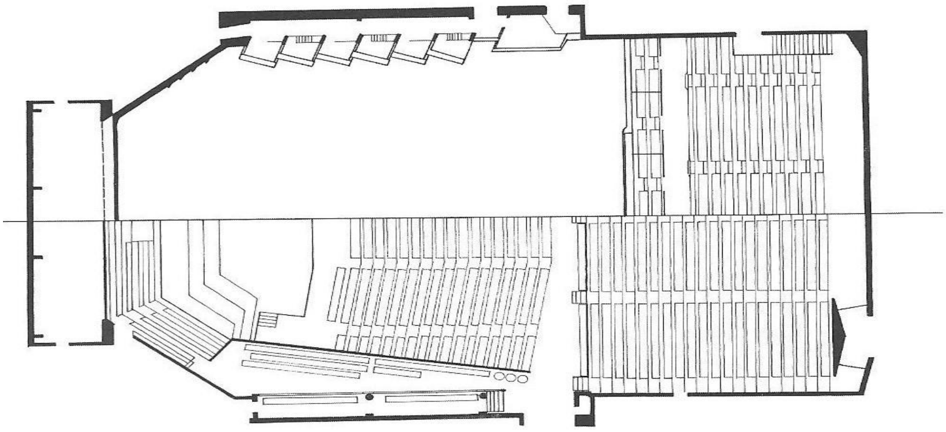
Appendix D: Plate 4

Royal Festival Hall, London

Royal Festival hall, London (Interior)



Royal Festival hall, London (Section)



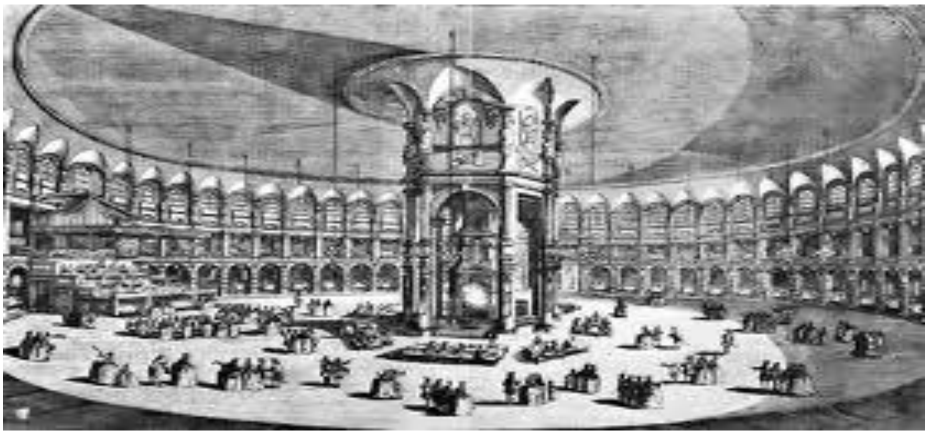
Royal Festival hall, London (Plan)

Source: [Barron, 2009]

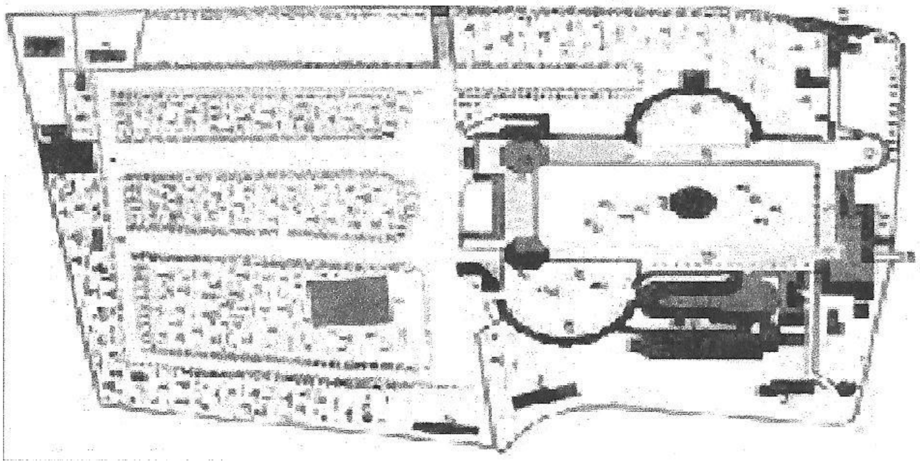
Appendix E: Plate 5

Vaux Hall Ranelagh Garden, London

Vaux hall Ranelagh garden, London (Exterior view) [Sidney,1955]



Vaux hall Ranelagh garden, London (Interior view) [Ukers, 2009]

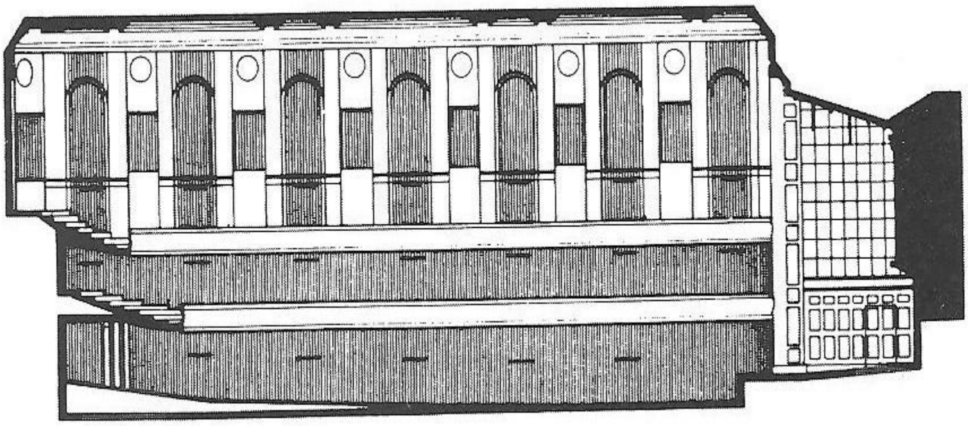


Vaux hall Ranelagh garden, London (Plan) [Sidney, 1955]

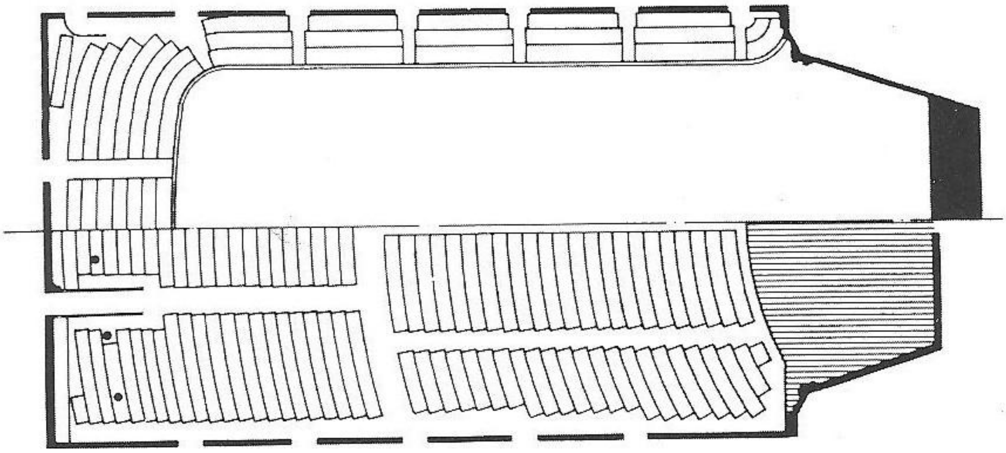
Appendix F: Plate 6

Boston Symphony Hall, Massachusetts

Boston symphony hall, Massachusetts (Interior view) [Egan, 2007]



Boston symphony hall, Massachusetts (section) [Barron, 2009]

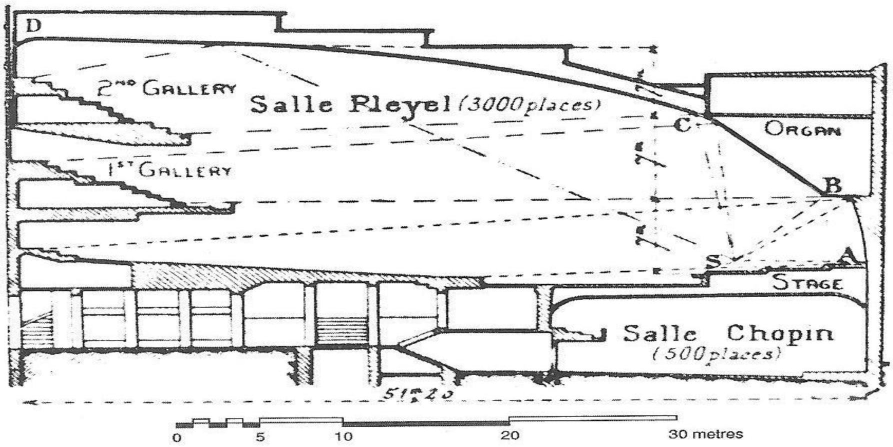


Boston symphony hall, Massachusetts (Plan) [Egan, 2007]

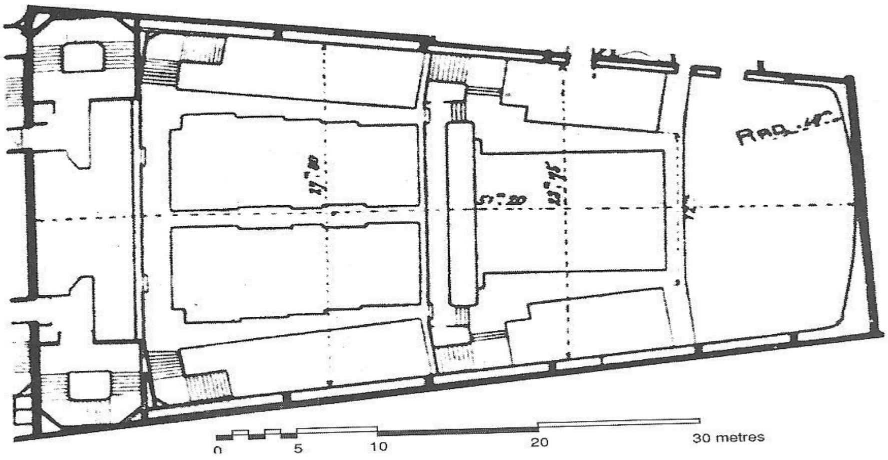
Appendix G: Plate 7

Salle Pleyel, Paris

Sale Pleyel, Paris (interior) [www.eurocheapo.com]



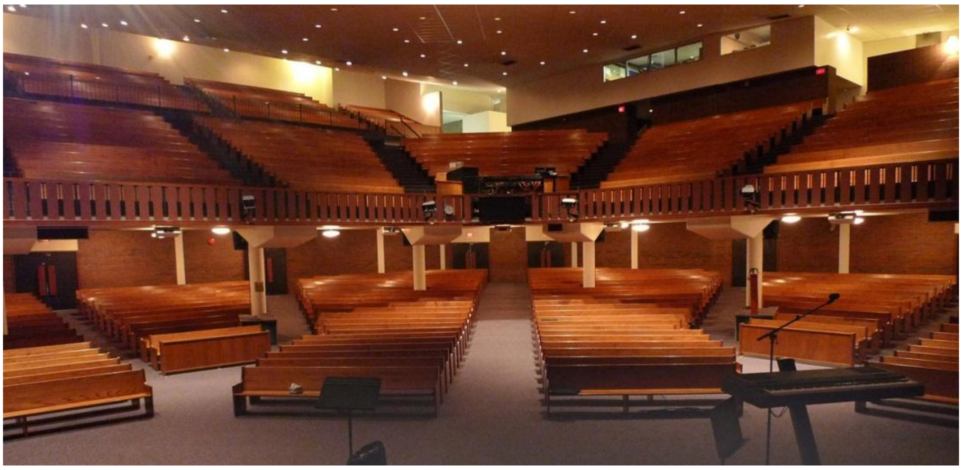
Sale Pleyel, Paris (Long section) [Barron, 2009]



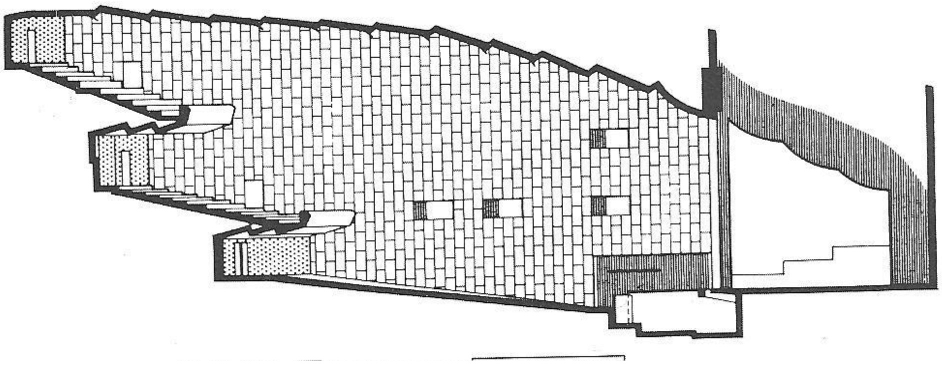
Sale Pleyel, Paris (Plan) [Barron, 2009]

Appendix H: Plate 8

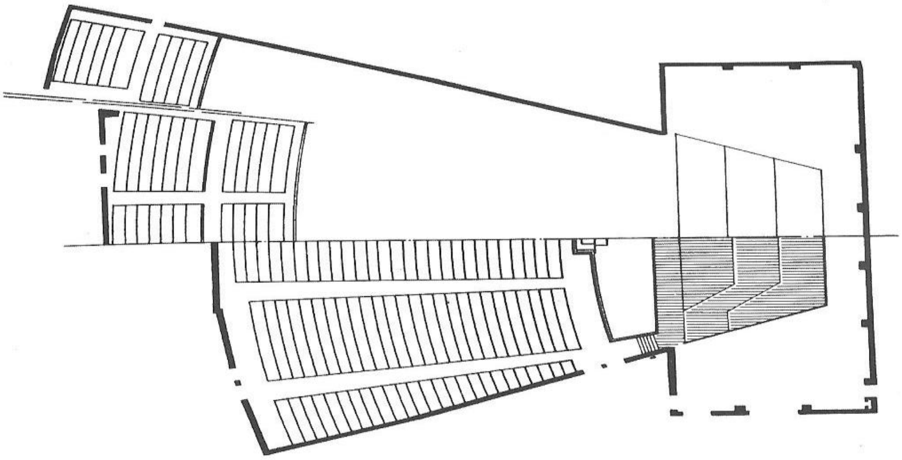
Alberta Jubilee Hall, Canada



Alberta Jubilee Hall, (interior) Canada [www.soundart.com]



Alberta Jubilee Hall,(Long section), Canada [Beranek, 2004]



Alberta Jubilee Hall,(Plan), Canada [Beranek, 2004]

Appendix I: Plate 9

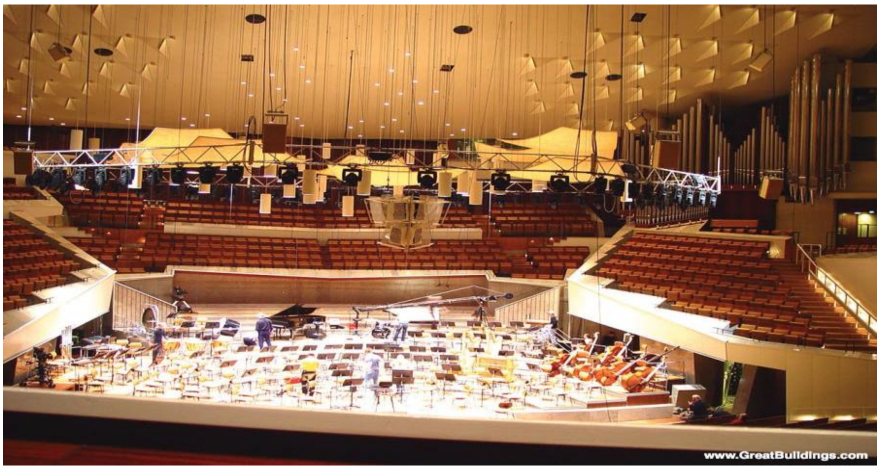
Beethovenhalle, Bonn, Germany

Beethovenhalle (Interior), Bonn [Monumnte-online Magazine, 2009]

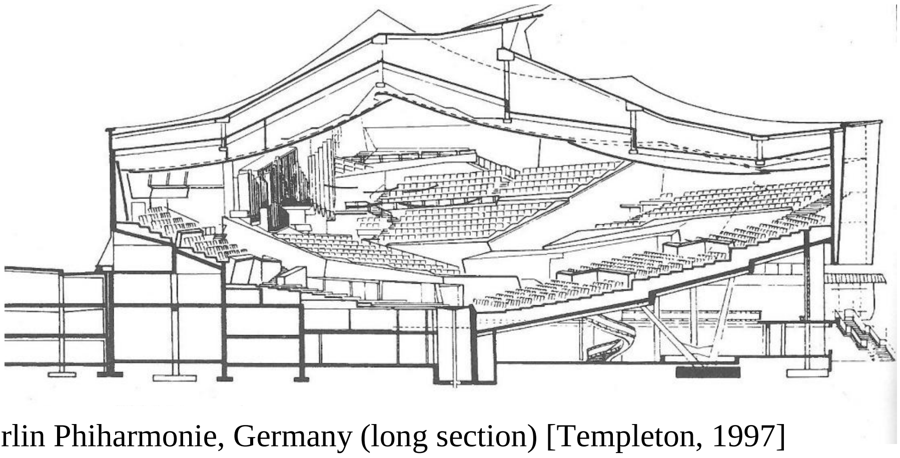
Beethovenhalle (Plan), Bonn [Monumnte-online Magazine, 2009]

Appendix J: Plate 10

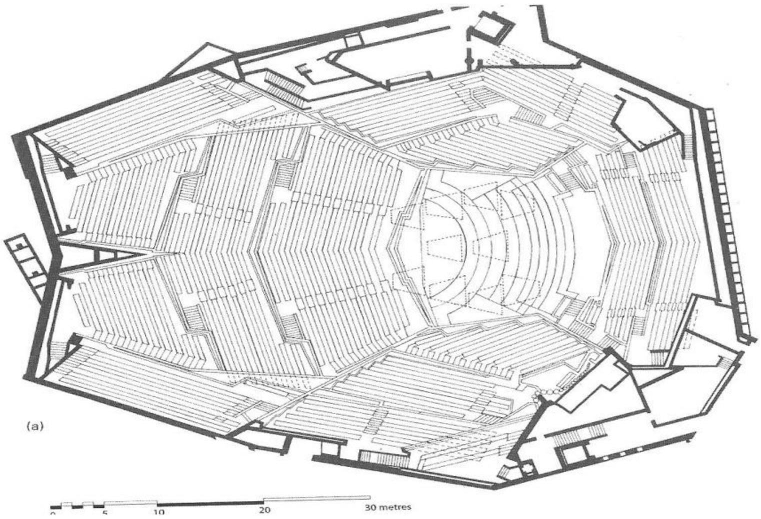
Berlin Phiharmonie of 1963, Germany



Berlin Philharmonie, Germany (Interior) [www.GreatBuildings.com,2009]



Berlin Phiharmonie, Germany (long section) [Templeton, 1997]

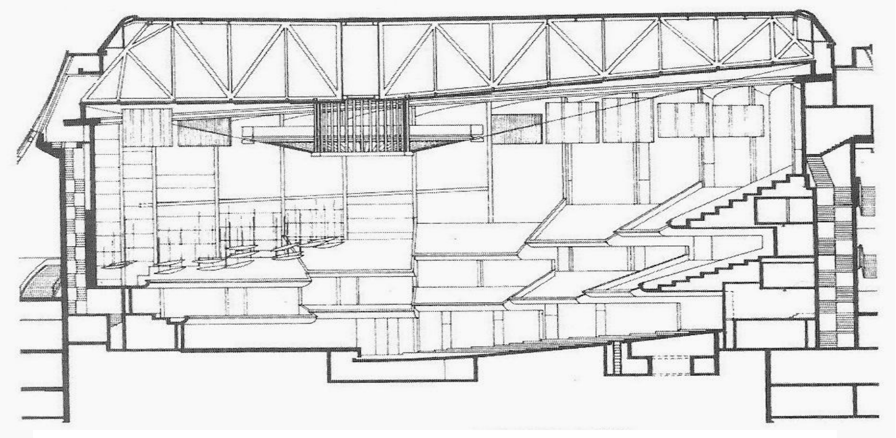


Berlin Phiharmonie, Germany (Plan) [Barron, 2009]

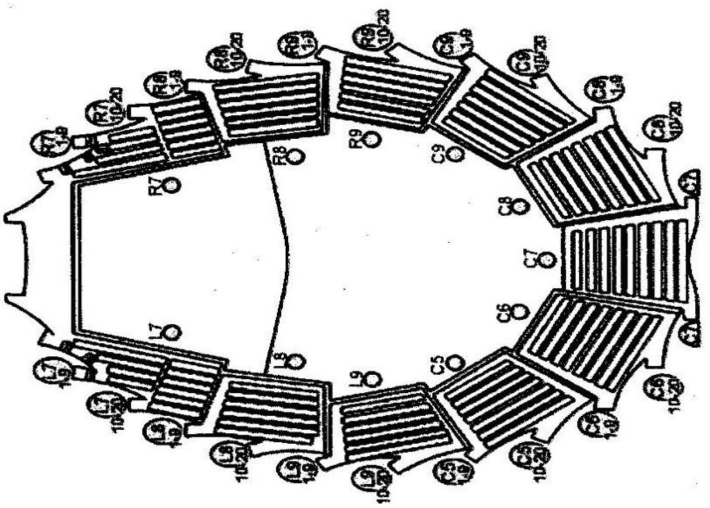
Appendix K: Plate 11

Roy Thomson Hall, Toronto

Roy Thomson Hall, Toronto (Interior) [www.cismf.ca, 2009]



Roy Thomson Hall, Toronto (long section) [Barron, 2009]

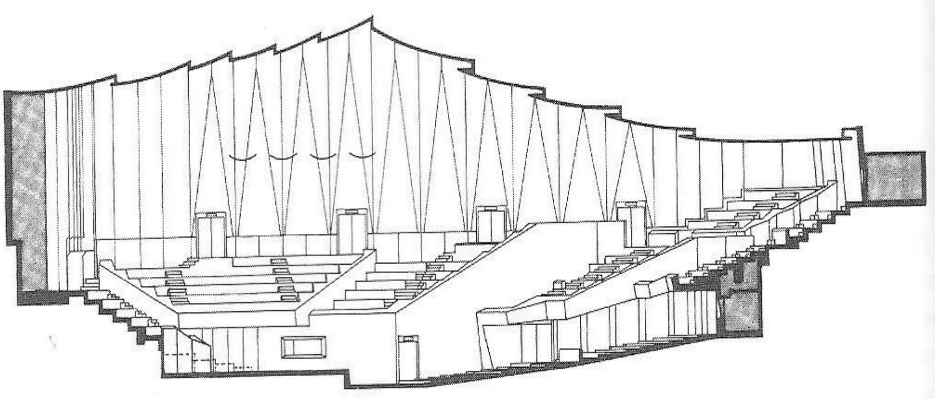


Roy Thomson Hall, Toronto (Plan) [www.gamestub.com, 2005]

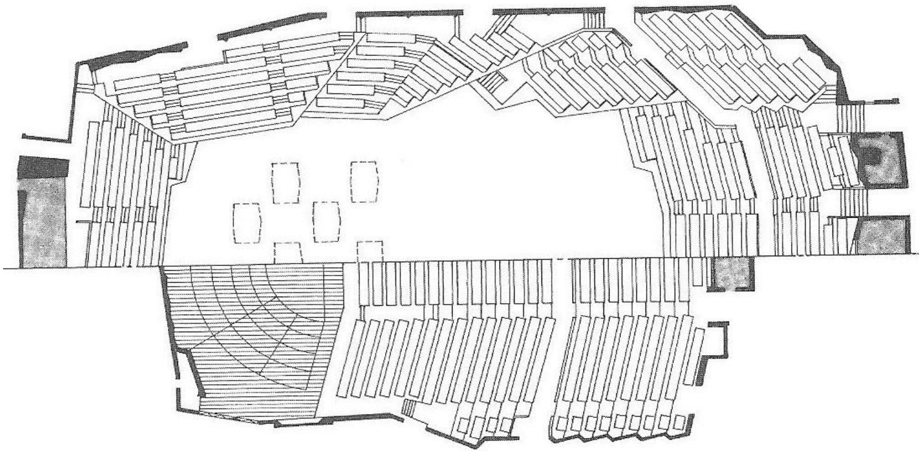
Appendix L: Plate 12

Suntory Hall of 1986, Tokyo

Suntory Hall, Tokyo (Interior)



Suntory Hall, Tokyo (long section)



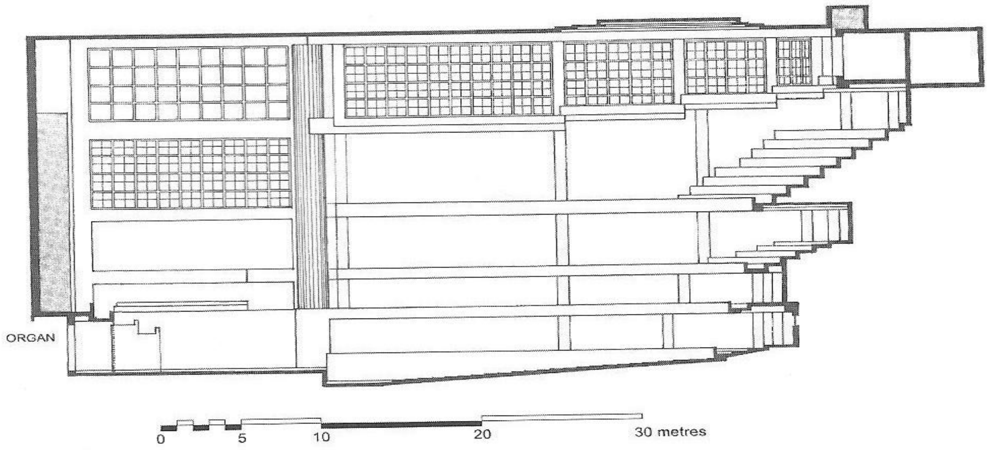
Suntory Hall, Tokyo (Plan)

[Source: www.nagata.co.Jp, 2007]

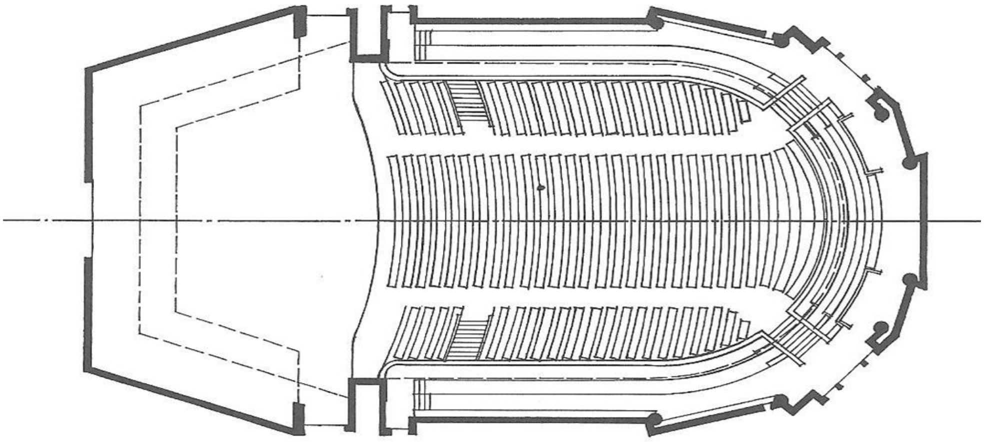
Appendix M: Plate 13

McDermott Concert Hall in Dallas, Texas

McDermott Concert Hall, Dallas (Interior)



McDermott Concert Hall, Dallas (Long Section)



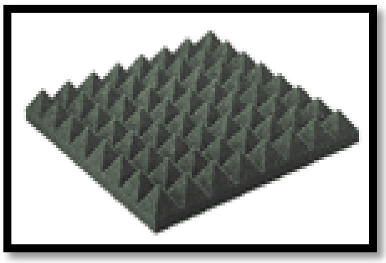
McDermott Concert Hall, Dallas (Main Plan)

[Source: Cavanaugh and Wilkes, 1999]

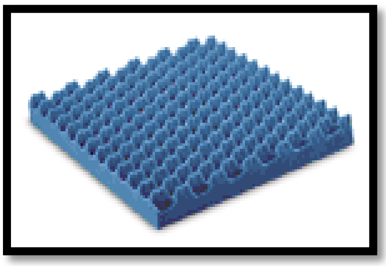
Appendix N: Plate 14

Selected Commonly Used Sound Absorbers In Structures

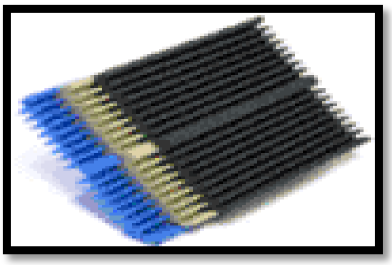
Polyurethane Foam



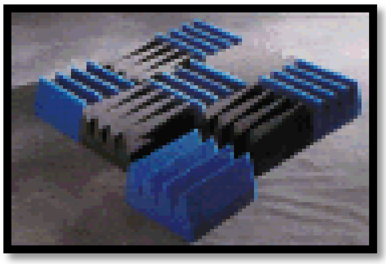
Polyurethane Pyramid



Polyurethane Pyramid



Cutting Wedge

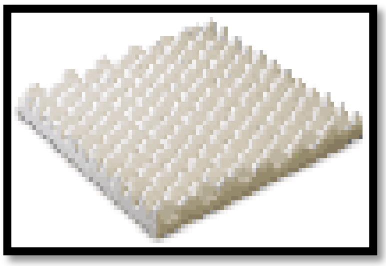


Max Wedge

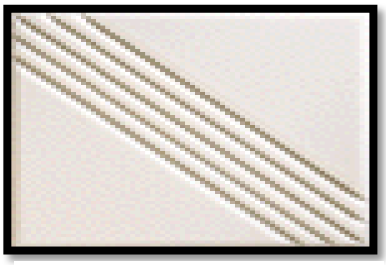
Bermuda Triangle Trap

Sound Cylinder

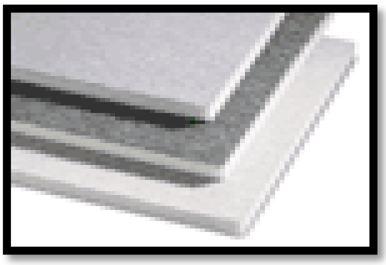
Fire-flex Foam



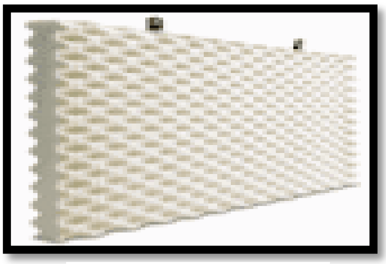
Fireproof (Class 1) Wall Panels



Cloudscape Ceiling Tiles (Drop-In)



Fab-TEC Fabric Covered Foam

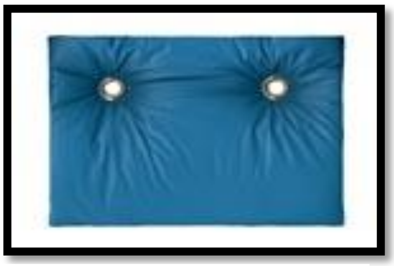


Hanging Baffles

Appendix O: Plate 15

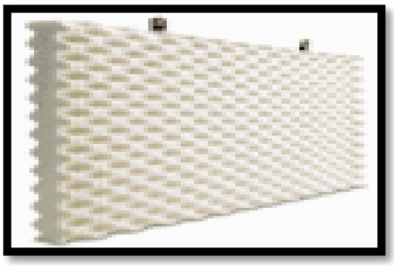
Ceiling Treatment

Baffles, Banners, Clouds and Tiles

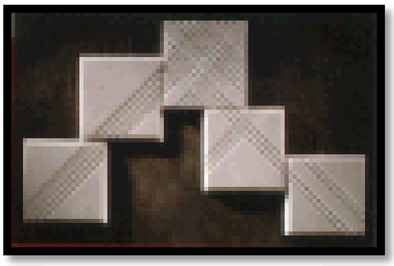


Cloudscape Hanging Baffles

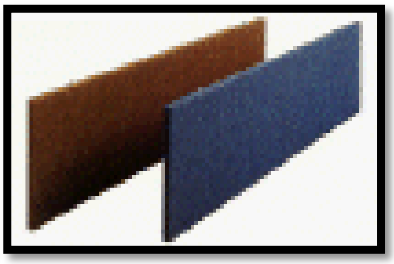
Cloudscape Banners



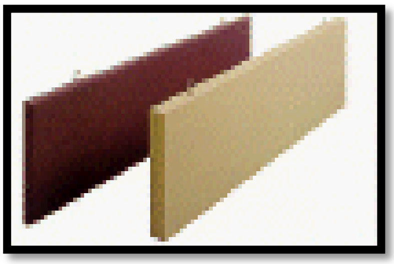
Wedge Foam Hanging Baffle



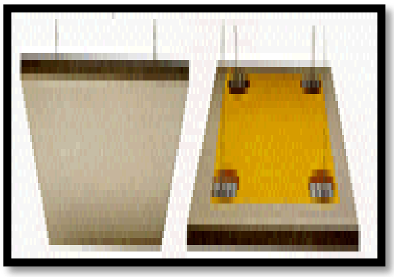
Cloudscape Tiles



Respond Hanging Baffles (Type I)

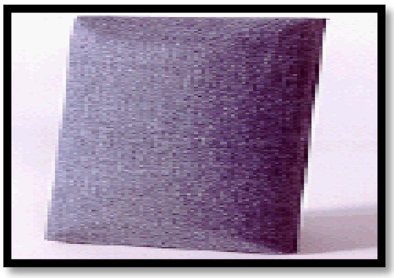


Respond Hanging Baffles (Type II)

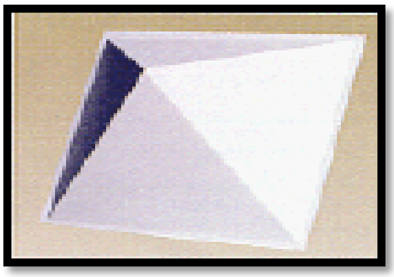


Response Ceiling Clouds

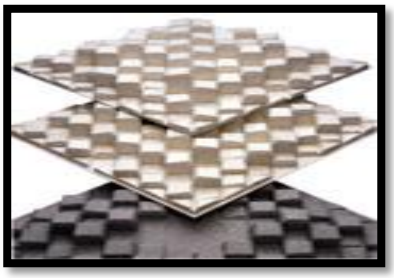
Ceiling Diffusers



Double Duty Diffuser



Pyramidal Diffuser



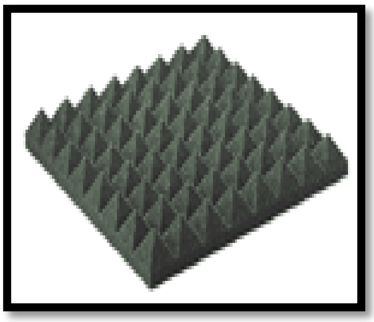
Art Diffuser

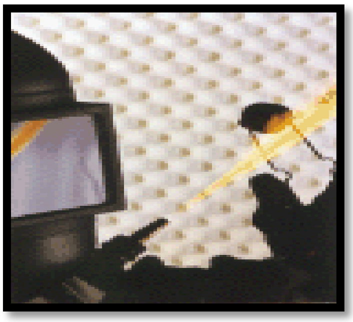
Appendix P: Plate 16

Wall Treatment

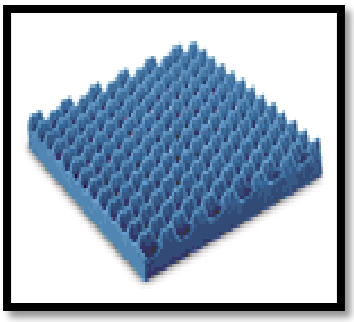

Respond Glass Fiber
Panel

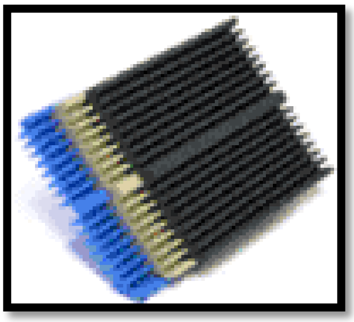

Quiet Louver Glass Fiber
Panel

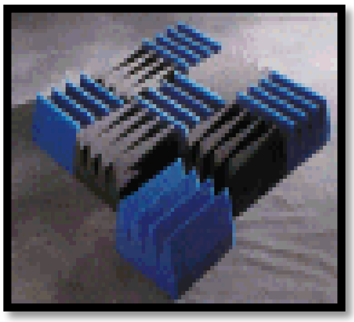

Pyramid Acoustical
Foam Panel


Fire-flex Class A
Acoustical Foam Panel


Quilted Fiberglass
Wall Blanked for
Industrial Environment


Wedge Acoustical Foam
Panel

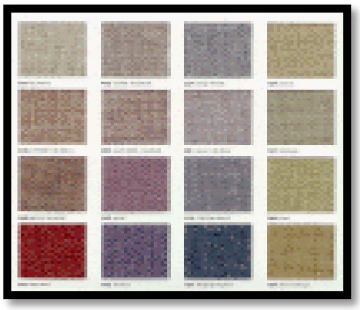

Cutting Wedge
Acoustical Foam


Max Wedge Acoustical
Panel (for low frequency
Absorption)

Appendix Q: Plate 17

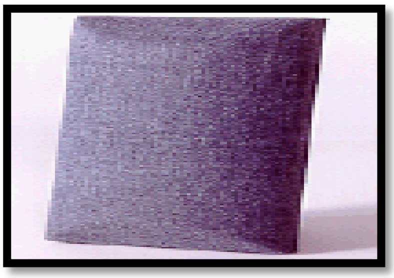
Acoustical Wall Fabric

Sound Channels Fabric
(For sound Absorption-
61 colors)

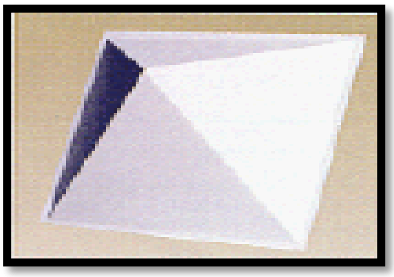


Guilford of Maine
(Acoustically
'transparent' fabric)

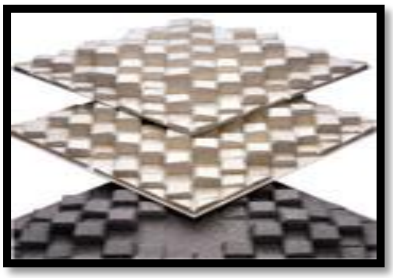
Wall Diffuser



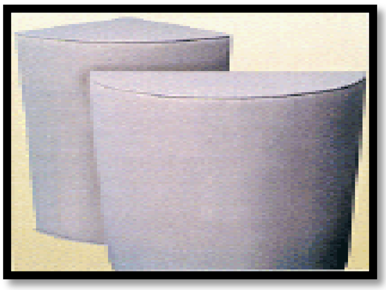
Double Duty Diffuser



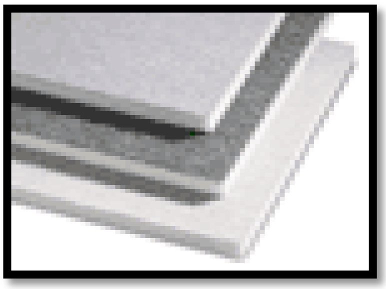
Pyramidal Diffuser



Art Diffuser



Geometrix
Broadband Absorbers
in quarter Round or
half-round



Bermuda Triangle Traps
(For Bass Trapping)

Fab Tee Panel