Technische Universität Graz

Institut für Architekturtechnologie

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Österreich

Dissertation

A METHODOLOGY FOR ACOUSTICALLY SUPERIOR SPACES

OR

AN ACOUSTICS HANDBOOK FOR ARCHITECTS

Dissertation submitted in partial fulfillment of the requirements for the academic degree of
Doctor of Engineering Sciences (Dr. techn.)
submitted by
Vesna Balta, Master of Architecture

approved by:
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Lector: Dr.sc. Graham McMaster

Date: October 2010.

DECLARATION

I hereby certify that the work reported in this dissertation is my own and that work performed by others is appropriately cited.

Ich versichere hiermit, diese Dissertation selbständig verfaßt, andere als die angegebenen Quellen und Hilfsmittel nicht benutzt und mich auch sonst keiner unerlaubten Hilfsmittel bedient zu haben.

Vesna Balta

ABSTRACT

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Building acoustics means, in the strictest and most commonly used sense, the necessary noise protection in space. Room acoustics means the enrichment of the space with high quality sound. In acoustics there are two major independent acoustic fields: room acoustics and building acoustics, also called architecture acoustics. Building acoustics forms a part of the obligatory study elements for buildings as it defines the physical characteristics of the building. Building acoustics, in most cases, is about most common problem of noise protection in the building and investigating which materials should be employed for getting the result aimed at. Building acoustics deals with how to minimize unwanted sound levels.

Room acoustics is obligatory only for architectural projects that have special acoustical purposes, such as concert halls, operas, theatres, etc. Room acoustics is, in fact, about how to obtain good hearing qualities in spaces with special acoustical purposes. Room acoustics deals with how to maximize the sound levels wanted; in fact, it deals with the augmentation of the sound field.

Building acoustics is part of engineering knowledge that every architect should be familiar with as it forms part of the obligatory study. It is clear that noise protection should be used in such as way as to ensure the health of the people using the space. Only after this first demand has been satisfied, noise, protection, does room acoustics come into consideration.

So, building acoustics is the necessary noise protection in space and room acoustics is the enrichment of the space with high quality sound.

In consequence of the above distinction, it is logical to start exploring acoustics as follows in this dissertation. In the introductory chapters in PART A the basic physical characteristics of the sound are discussed. Sound is presented in its physical base. In PART B room acoustics is presented and explained. PART C is about the methodology of designing and the use of room acoustics rules. In PART D there are seven examples, and explanations about the acoustics of a major group of buildings are presented.

Keywords: building acoustics, room acoustics, sound, basic physical characteristics of sound, methodology of architectural design, acoustic building examples.

ZUSAMMENFASSUNG

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Bauakustik bedeutet, in eng und am häufigsten gebraucht Anwendung, erforderliche Lärmschutz im Raum. Raumakustik bedeutet mit qualität Klang Raumanreicherug.

Im Acoustik es gibt zwei grosse unabhängig acoustische Felder: Raumakustik und Bauakustik die often man auch Architekturakustik nähnt.

Bauakustik ist ein Teil von obligathorische Elaborat für Bauen weil die die physikalische Characteristiken des Gebäude definiert. Bauakustik zumeist von allgemein üblich Lärmschutzprobläme in Gebäude handelt und auch mit Ausforschung von Materiallien die sollte für bezielte akustische Resultate gebraucht werden. Bauakustik handelt um wie unerwünscht Schallpegel zu vermindern.

Raumakustik ist nur für architektonische Projekten die speciale acoustische Anwendungen haben obligatorish, zum beispiel für Konzerthalle, Opera, Theater, usw. Raumakustik ist eigentlich wie zu gute Hörqualität in Raume besondere akustische Zweck beschaffen. Raumakustik handelt mit wie gesuchene Schallpegel zu erhöhen; dass ist in einsatz die Schallfeldsaugmentation.

Bauakustik ist ein Teil von technische Erkentniss die von jeder Architekten, weil dass ein Bauteil von obligatorischen Elaboraten ist, bekannt sollten wird. Es ist klar dass Lärmschutze sollte wegen des Gesundheits in Raum verwendet wird. Nur nach Erholung dieser Erforderung, Lärmschutz Erforderung Raumakustik kann beobachcten werden.

So, Bauakustik ist obligathorische Lärmschutz im Raum und Raumakustik ist Anreichung des Räumes mit Qualitätsklang.

Aus oben schriftene es ist logisch mit eine Forschung von Akustik in Disertation als wie folgt zu beginnen. In dem Anfang Titel PART A es geht um grundsätzliche physikalishe Klangcharakteristiken. Der Klang wird mit seinem physikalische Basis presentiert. Im PART B Raumakustik wird presentiert und erklärt. PART C handelt mit architektonische Entwurfsmethoden und raumakustische Regeln Benutzung. Im PART D sieben echtige Akustikbauen Beispile von hauptsächtliche Baugruppen und Beschreibungen presentiert werden.

Schlagwörter: Bauakustik, Raumakustik, Klang, grundsätzliche physikalishe Klangcharakteristiken, Akustikbauen Beispile

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And at last, from a personal aspect I would like to thank to my family and parents for unconditional support.

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INTRODUCTION

In acoustics there are two major independent fields: room acoustics, which is a narrower part of architectural acoustics, and building acoustics, or noise protection. Building acoustics or noise protection is a part of the obligatory studies for buildings as it defines physical characteristics of the building.(British Gypsum; Web Page;*Building acoustics_term*)

Noise protection in a building investigates which materials should be employed for getting the result aimed at. The goal of noise protection is to minimize unwanted sound levels.

Architectural acoustics or room acoustics is the relationship between a sound produced in a space and its listeners, and is of particular concern in the design of concert halls and auditoriums. Architectural acoustics includes room acoustics, the design of recording and broadcast studios, home theaters, and listening rooms for media playback.(Britannica; Web Page;*Architectural acoustics_term*)

Architectural acoustics is, for some authors, a wider term than room acoustics.

Architectural acoustics must be taken into consideration only for architectural projects that have special acoustical sound purposes, such as concert halls, operas, theatres, etc. Architectural acoustics is, in fact how to obtain good hearing qualities in spaces with special acoustical purposes. Architectural acoustics deals with how to maximize the wanted sound levels; it deals in fact with augmentation of the sound field. In further observations the terms architectural acoustics and room acoustics will be used synonymously.(Wikipedia; Web Page;*Architectural acoustics vs room acoustics*)

Every architect should be familiar with the concept of building acoustics as it is the part of the obligatory development plan. Protection against must be ensured for the sake of human health. Only this first demand has been met, the requirement for protection against noise, does room acoustics start to be considered. Building acoustics refers to the necessary noise protection in a space while room acoustics deals with the enrichment of a space with sound.

This dissertation will explore room acoustics, in other words, architectural acoustics, in depth. Noise protection or building acoustics will be mentioned only when necessary for the explanation of architectural acoustics conditions.

Also, the field of exploration is going to be restricted to sounds that are not amplified or electronically enhanced.

This dissertation as a result will endeavour to answer a question, or thesis, and will also have a goal. The goal is going to be gathering and purifying important facts for sound quality.

The major question is to be asked: Can methods be developed to provide sound superior spaces? In the search for the answer to this question a wide range of sound knowledge should be primarily discussed. The dissertation is oriented towards the revelation of contemporary findings in the field of acoustics through an exploration, through the eye of an architect. The goal is to gather the latest findings in architectural acoustics and to summarise them into the form of a handbook. The goal is also to present this exploration through its basic parts which are purified of unnecessary inputs that do not contribute in any great amount to answering the thesis or the question asked.

From everything explained above, it is logical to start exploring acoustics as follows. In the introductory chapters in PART A, the basic physical characteristics of sound are explained. Sound is presented in its basis in physics.

In PART B room acoustics is presented and explained.

PART C is about the methodology of projecting and the use of room acoustics rules.

In PART D seven real examples of a major group of buildings are presented and discussed.

The final chapter of the text answers the questions about contemporary methods in architectural acoustics and whether it is possible to define a useful methodology. The conclusion also summarises the facts about high quality sound presented.

PART A Fundamentals of sound physics

SECTION A 1 Sound wave basic terms

See generally(Wolfe;Web Page;School of Physics; 2004.),(Cavanaugh & Wilkes;Book;Architectural Acoustics: Principles and Practice; 1999),(Schricker;Book;Kreative Raum -Akustik: für Architekten und Designer; 2001.), (Grueneisen;Book;Soundspace: Architektur für Ton und Bild; 2003), (Web Page;Acoustics), (Bellingham;Web Page;*Room Acoustics*; 2003-2006.).

Sound is constituted in a physical sense by waves, in fact any wave is a mechanical disturbance; waves are changes in an elastic medium. Sound is produced when the air is disturbed in some way, for example by a vibrating object. Elastic media are grouped into solids, fluids and gas.

To understand complex relations between a person and sound source in field of acoustics basic physical rules for sound should be defined as a basis for further understanding and exploration.

Figure A- 1 Development of sound wave illustrates tuning fork that produces pure tone.

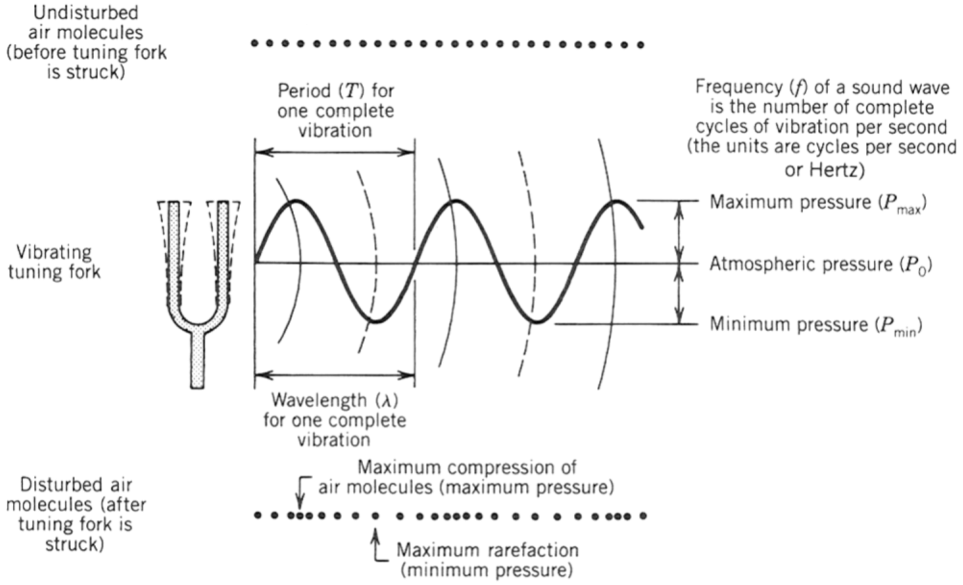


Figure A- 1 Development of sound wave.

(Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999)

A speaker cone from a hi-fi system serves as a good illustration. It may be possible to see the movement of a bass speaker cone, providing it is producing very low frequency sound. As the cone moves forward the air immediately in front is compressed causing a slight increase air pressure, it then moves back past its rest position and causes a reduction in the air pressure, in other words rarefaction. The process continues so that a wave of alternating high and low pressure is radiated away from the speaker cone at the speed of sound.

Figure A- 2 Sound wave transmission shows that “highs and lows” of sound waves in real are transponated in the “ forward direction an transversal type of wave for scientific use.
Sound is in fact longitudinal wave. In this figure it is evident how we transform longitudinal waves, in which way sound waves in real space and time conditions are moving, into transversal type of wave for scientific use.

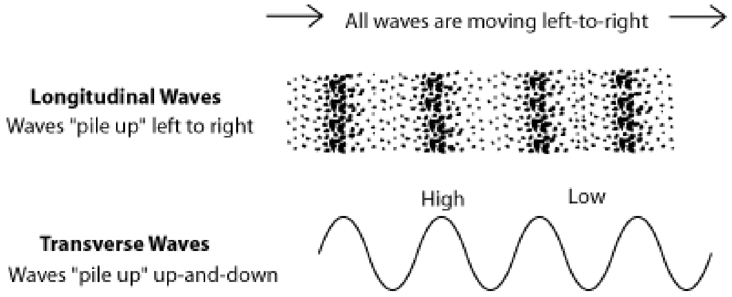


Figure A- 2 Sound wave transmission.
(Schmidt-Jones;Web Page;*Acoustics for Music Theory*; 2007.)

Longitudinal wave is the kind of wave when you try imagining yourself as one of the particles that the wave is disturbing, like for example a water drop on the surface of the ocean, or an air molecule. As it comes from behind you, a transverse waves lifts you up and then drops down; a longitudinal wave coming from behind pushes you forward and pulls you back. Even though sound waves are longitudinal waves they are shown in diagrams as they are transversal waves to clearly show their characteristics in this way: displacement is biggest, furthest from "normal" at the highest and lowest points of the wave. In a sound wave, then, there is no displacement wherever the air molecules are at a normal density. The most displacement occurs wherever the molecules are the most crowded or least crowded.

We need to clarify basics and go into research .Therefore basic characteristics of sound are: the speed of sound, frequency, length of the wave and after that sound pressure and sound pressure level.

Sound waves can like other types of wave move in different ways: like longitudinal or transversal wave. For researching room acoustics longitudinal waves are important because they move in longitudinal manner, and transversal waves are in fact movements of sound energy through solid medium and people experience them as vibration.

Basic rules of sound are discussed from different aspects depending in which research field the term of sound is placed. Therefore, if talking about the field of radiology than for researching of sound other characteristics are major than characteristics of sound in field of music, phonetics, acoustics etc.

Also, here it should be pointed out that the sound has its objective and subjective basis. Subjective basis is relevant for relationship between a person and sound, and objective basis are physical entities that are purred from minor distortion and differences that may be result of personal relation to sound.

A 1.1 Particle velocity and speed of sound

Sound is mechanical oscillation. Oscillation in fact means moving of a particle through elastic medium that is actuated from the state of inaction with some external action. Particle velocity is the velocity v of a particle, real or imagined in a medium as it transmits a wave. In many cases this is a longitudinal of pressure as with sound. Particle velocity v should not be confused with the speed of the wave as it passes through the medium, i.e. in the case of a sound wave; particle velocity is not the same as the speed of sound c. (Wikipedia; Web Page;*Sound velocity*)

Figure A- 3 Speed of sound in some materials illustrates speed of sound wave in different materials Particle velocity is different in different media, so for water it is no more 340 m/s but 1481 m/s if temperature of water is 20 °C.

Material	Speed of sound
Rubber	60 m/s
Air at 40^{o}C	355 m/s
Glass	4540 m/s
Lead	1210 m/s
Stone	5971 m/s
Copper	3100 m/s

Figure A- 3 Speed of sound in some materials.
(NDT Resource center; Web Page;*Sound*)

Speed of sound is more exact measurement than particle velocity because in speed of sound equation there is also information about the temperature of the medium. In fact it is information about small delay of the sound. The equation for speed of sound in air when humidity is 0% is:

c_0= 331+ 0, 6 t (m/s)

t= temperature of the medium

This formula is valid only for gas medium state, and can not be used for water and solids because water is dispersive type of medium and in solid the speed is not dependent on temperature but on density, so other formulas are applied.

Explaining further the standard speed of sound formula for gas, one can see that for every change of speed of sound of 1% there should be a difference of the temperature of 6 Celsius degrees. So, the speed of sound is increased for 0, 18 % if the temperature difference is 1 Celsius degree. (Fasold;Book;*Scallschutz und Raumakustik in der Praxis: Planungsbeispiele und konstruktive Lösungen*; 1998.)

Temperature is not alone in affecting the speed of sound, other characteristics of medium contribute to total speed of sound. These are: air humidity, but its contribution is not that big as of temperature. For the field of room acoustics where we assume always constant temperature we use a value for speed of sound of 340 m/s

The speed of sound in air at a temperature of 0 deg C and 50% relative humidity is 331.6 m/s. The speed is proportional to the square root of absolute temperature and it is therefore about 12 m/s greater at 20degC. The speed is nearly independent of frequency and atmospheric pressure but the resultant speed of sound may be substantially altered by wind velocity.(Meyer;Book;*Kirchenakustik*; 2003)

SECTION A 2 Frequency and wavelength

The aspect of evenly-spaced sound waves is wavelength or the spacing between the waves, the distance between, for example, one high point and the next high point. (Schmidt-Jones;Web Page;*Acoustics for Music Theory*; 2007.)

Figure A- 4 Wavelength, Frequency and Pitch.The distance is always measured between same phases. It affects the pitch of the sound; the closer together the waves are, the higher the tone sounds.

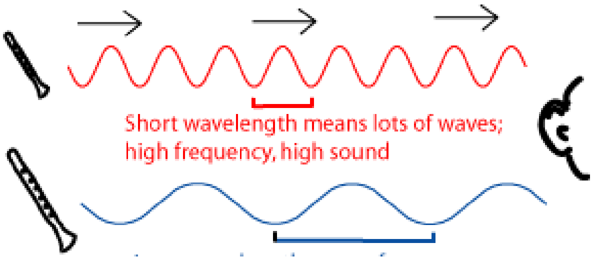


Figure A- 4 Wavelength, Frequency and Pitch

(Schmidt-Jones;Web Page;Acoustics for Music Theory; 2007.)

All sound waves are traveling at about the same speed - the speed of sound. So waves with a shorter wavelength arrive more often (frequently) than longer waves. This aspect of a sound - how often a peak of a wave goes by, is called *frequency*. We measure it in *Hertz*, which is how many peaks go by per second. $Hz=\frac{1}{s}$.

Higher frequency means that the sound wave is oscillating very fast, so the density of the sound field is thicker, wavelength is smaller and the ultimate effect is higher pitch. Lower frequency means that waves are oscillating slowly, the sound field is thinner and so the wavelength is longer and the ultimate result is lower pitch.

A 2.1 Wavelength λ

Wave length is the distance, interval between two particles of the wave that have the same period of oscillation, in other words they are in the same phase. This is the distance between two particles that are called Maxima, or distance between two particles called Minima. Wavelength is connected to term speed of sound c (m/s) and frequency f (Hz), in other words T period of oscillation(s). The equation is:

$$\lambda=cT=\frac{c}{f} \text{ (m)}$$

The relation between frequency f and wavelength λ are going to be clarified.

Differences between wavelengths in different frequencies are substantial. (Schmidt-Jones;Web Page;*Acoustics for Music Theory*; 2007.)

How we calculate the wavelength? Simply, it is dividing the speed of sound of 340 m/s with the frequency and so we will get the wavelength. For a frequency of 1000 Hz the result is wavelength of 0.34 m. By frequency of 100HZ wavelength is 3, 4 m, by frequency of 1000 Hz the length is 34 cm and by frequency of 10 000 Hz 34 mm.

Figure A- 5 frequency and wavelength and their dependency is in fact nomograph for quicker insight into relation between frequency and wavelength without calculating each wavelength.

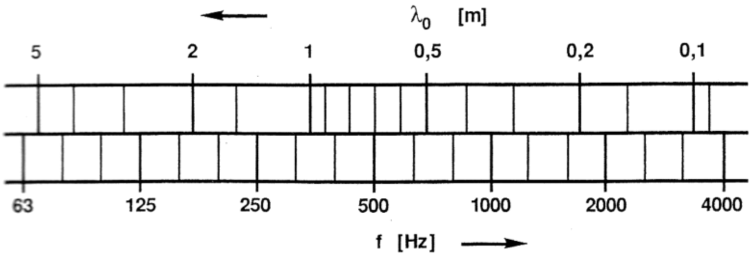


Figure A- 5 frequency and wavelength and their dependency. Figure translated by the author of the dissertation from the reference (Fasold;Book;*Scallschutz und Raumakustik in der Praxis: Planungsbeispiele und konstruktive Lösungen*; 1998.)

From the example and the picture it is clear that the range of wavelength is rather big from 21 m and 25 cm for frequencies of 16 Hz and on the diametrical side for human threshold of 20 000 Hz the wave length is 17 mm. For research in Room acoustics the range of wave lengths is shorter, concretely for the tone of 125 HZ 2.72 m and for the tone of 4000 Hz it is 85 mm.

In room acoustics wave length is therefore very significant information because of the range between 2.72 m to 8.5 cm. Because of that important element of the sound field geometry of space is substantial, its material finishing and all interior furniture are significant because of the reflection. In general: if the pitch is higher, then the wavelength is shorter.

It is significant that in designing space high frequencies do not have an influence in geometry of the space, neither on details, middle range totally falls into substantial facts for space determination, while for deep frequencies interior elements are rather small and therefore they do not contribute to deep frequencies. The conclusion is that in room acoustics we should focus on the range of middle frequencies from high c'' in tenors voice which is 524 Hz to high c''' in soprano voice in frequency 1057 Hz. So, the middle frequency is from 500 or more often 1000 Hz. (Meyer;Book;*Kirchenakustik*; 2003)

A 2.2 Frequency ranghs: human thresholds, infrasound, ultrasound, Human hearing

See generally (Web Page;*Acoustics*), (Fasold;Book;*Scallschutz und Raumakustik in der Praxis: Planungsbeispiele und konstruktive Lösungen*; 1998.).

Sound field less than 16 Hz is called infrasound. Infrasound can not be heard by the human ear but could be felt it in terms of vibration. Earthquake is a phenomenon with sound energy in the field of infrasound. Infrasound sometimes results naturally from severe weather, surf, lee waves, avalanches, earthquakes, volcanoes, bolides, waterfalls, calving of icebergs, aurora, lightning and sprites.

Sound energies over 20000 Hz (20 KiloHertz or 20 kHz) are in the field of ultrasound. This sound field segment is mainly used for medicine for various deep screenings and diagnostics. Usage of ultrasound in peacetime and wartime purpose. The usage is also in visualization, alarm appliances, wildings, purging, emulgating etc. In hydroacustics, underwater transport of information and in fishing. It has a wide range of use in whole fields of medicine like in diagnostics, therapy, sugery. Usage of ultrasound in development of technology is in general present in contemporary science. (Wikipedia; Web Page;*Infrasound*)

The frequency range of sound audible to humans is approximately between 20 and 20,000 Hz.

Figure A- 6 Frequency audible range shows the whole audible range and frequency dependend ranges shuch as vocal and orchestra ranges.

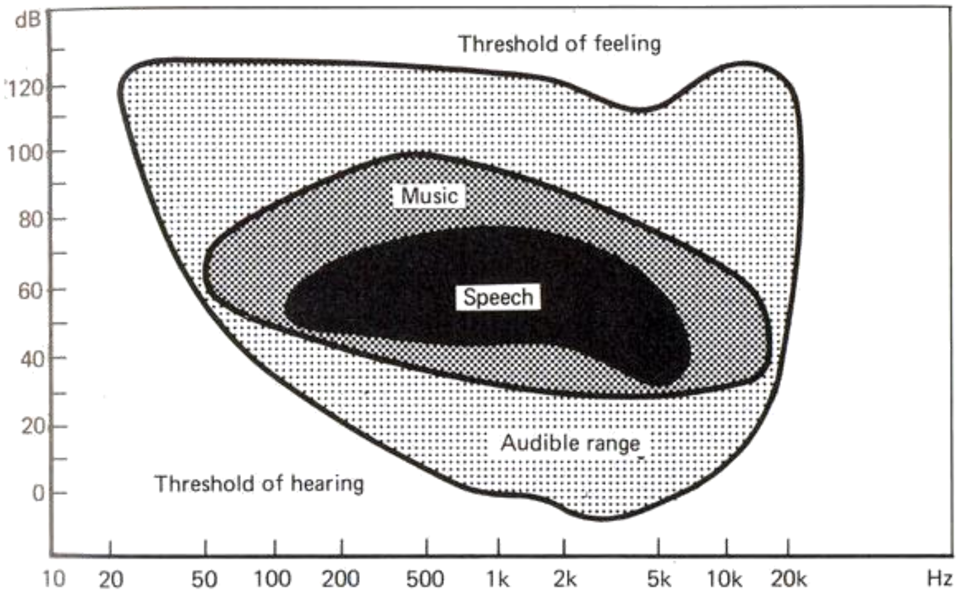


Figure A- 6 Frequency audible range.

(Decimin Control Systems P. Ltd. ; Web Page;*Technical information*)

This range varies by individual and generally shrinks with age. Infrasound is sound with a frequency too low to be detected by the human ear , less than approximately 20 Hertz. Infrasound is characterized by an ability to cover long distances and get around obstacles with little dissipation. Ultrasound is sound with a frequency greater than the upper limit of human hearing, approximately 20 kiloHertz. Some animals, such as dogs, dolphins, and bats, have an upper limit that is greater than that of the human ear and thus can hear ultrasound.

Namely, building acoustics is dealing with in segment of frequencies of 100 Hz to 3200 Hz,Room acoustics is dealing with in segment of frequencies from 125Hz to 4000 Hz, Noise protection with frequencies from 62, 5 Hz to 8000 Hz.

Figure A- 7 Frequency range and acoustics illustrates technical disciplines and their relations.

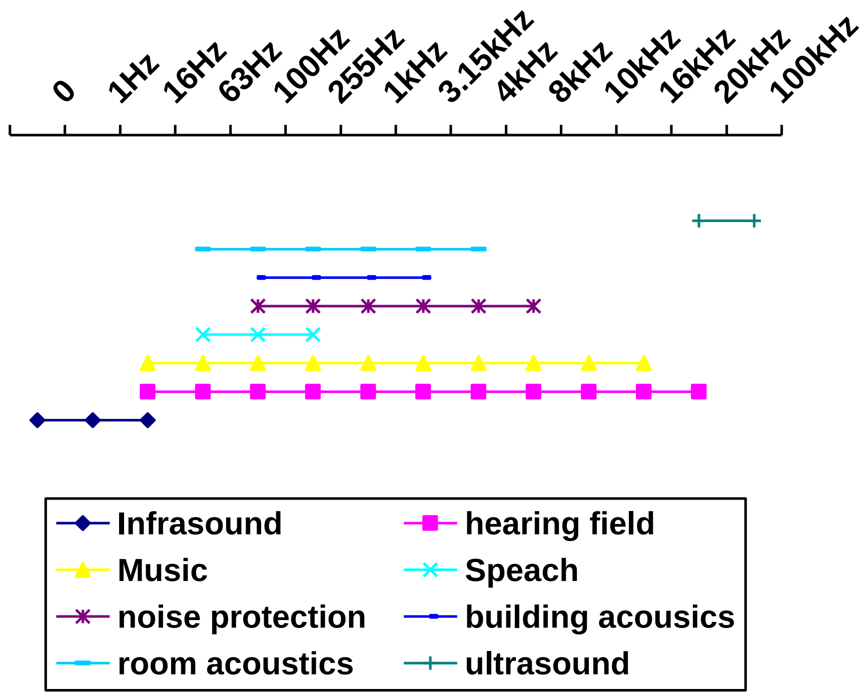


Figure A- 7 Frequency range and acoustics. Figure was done by the author of the dissertation based on data from reference (Fasold;Book;*Scallschutz und Raumakustik in der Praxis: Planungsbeispiele und konstruktive Lösungen*; 1998.)

People can hear sounds that range from about 16 to about 20,000 Hertz. Older persons hear about only to 17 000 Hz.

Figure A- 8 Hearing loss depending on person’s age

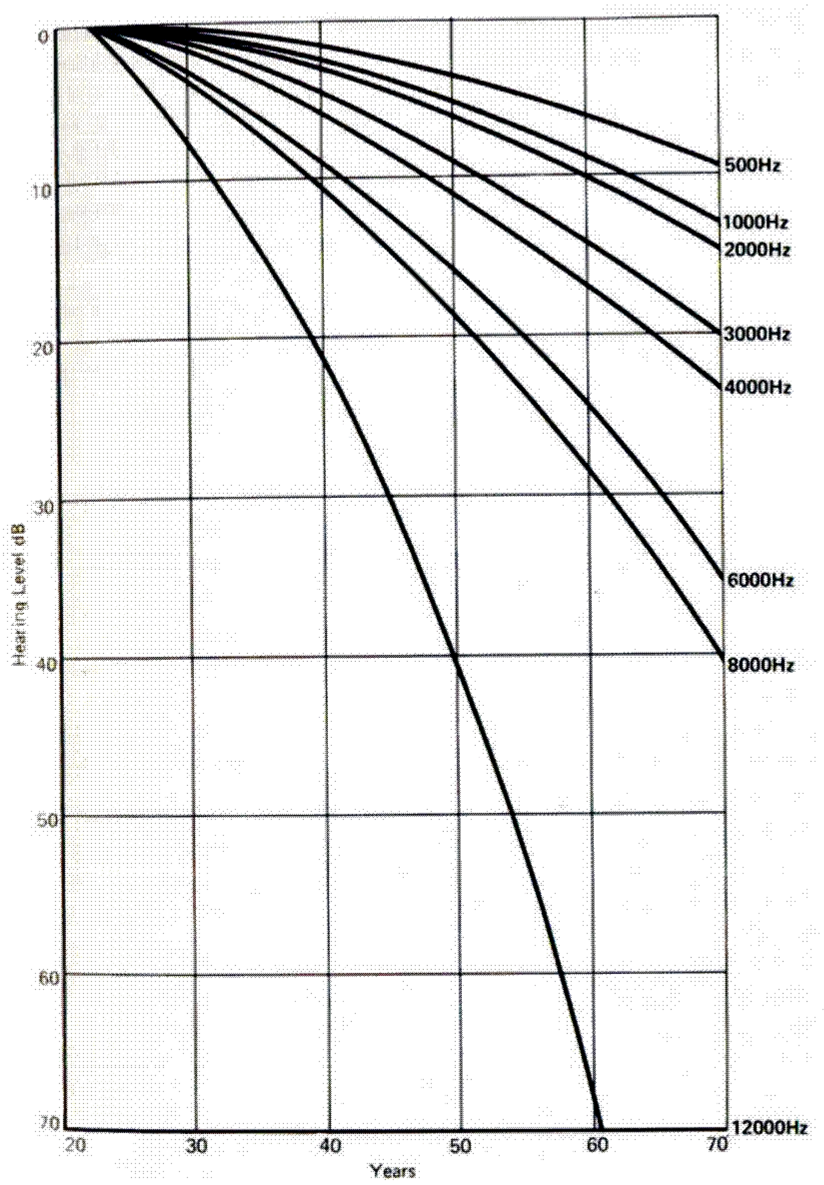


Figure A- 8 Hearing loss depending on person’s age.

(Decimin Control Systems P. Ltd. ; Web Page;*Technical information*)

Since the sounds are traveling at about the same speed, the one with the shorter wavelength "waves" more frequently; it has a higher frequency, or pitch. In other words, it sounds higher. T is the period of duration of one oscillation in the same phase, and the relation is measured with equation $T=\frac{1}{f}$ (s).

The human ear can easily distinguish two pitches that are only one Hertz apart when it hears them both, but it is the very rare musician who can hear specifically that a note is 442 Hertz rather than 440 Hertz. So, we can hear the difference but we can not easily say what the tone's name is.

The ability to identify any pitch heard or produce any pitch referred to by name is called absolute pitch or perfect pitch and is used by musicians.

When we are talking to each other, in eye to eye relation the amount of information that we get from hearing the sound is not that big as it is in communication that is based on collective listening to a speech, to music, etc. Namely, when we speak in close communication only about 7 percent verbal (words only) and 38 percent vocal (including tone of voice, articulation, accentuation, inflection, and other sounds) and 55 percent nonverbal. So, 93 percent of message we have heard is in other person's tone, accentuation, and body talk. When we are collective listeners then we can not see that much of person's attitude, subtle body talk in his or her face and body postures. So, as collective listeners we collect more information from the sound that we get in the case of close communicating.

Singers and actors are trained through their education to focus on the sound they articulate so that they could be heard from larger group of listeners and not only to give their emotion through the expression of the face and body but through the dynamics of voice. The fact is that we understand better, or get more precise information when listening in real time terms and in the same space with speaker, actor or musician. The feeling is better than listening to recorded one on tape. On tape, that part of body language is not involved. Opera singers are trained to carry the meaning and the feeling of the composer through musical phrase and minimize body language. With training, that way they significantly expand their volume of the voice.

A 2.3 Frequency and music

See generally (Fasold;Book;*Scallschutz und Raumakustik in der Praxis: Planungsbeispiele und konstruktive Lösungen*; 1998.).

For room acoustics purpose we distinguish frequencies in octave bands because further to that we deal with speech octaves and music octaves for male and female voice.

Figure A- 9 Frequency range for instruments and human voice

In music the term frequency is divided into octave bands. Bands are duplicating or halving of frequency. It is frequency relation of 1:2. Third is 1/3 of a band, so frequency relation is 1:1,28.

We come to the conclusion that if we use the knowledge about speed of sound and its frequency than if speed of sound changes for 6% then we have alteration of the tone height of ½ a tone.

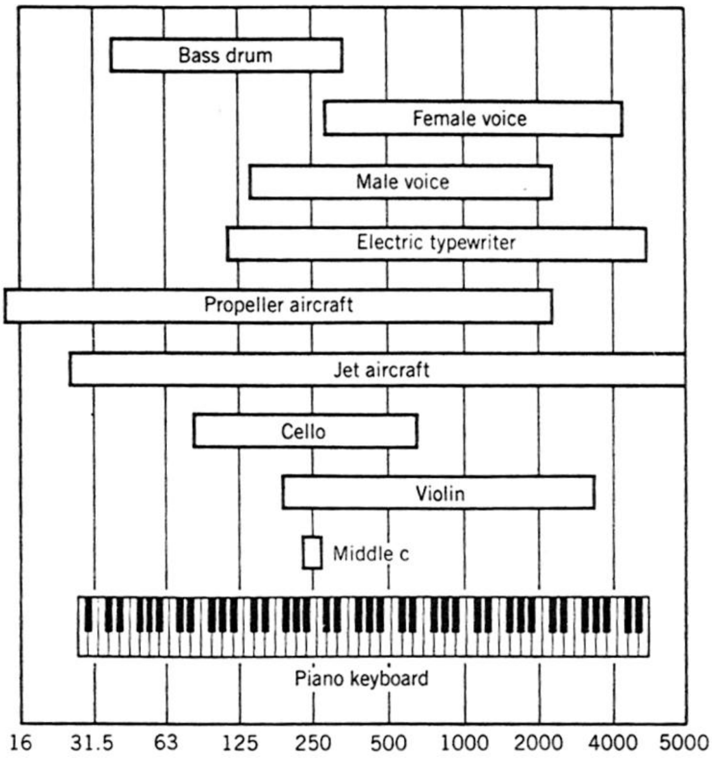


Figure A- 9 Frequency range for instruments and human voice.
(Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999)

A 2.4 Frequency and speech or singing formants

See generally (Wikipedia; Web Page;*Formant*), (Wikipedia; Web Page;*Voice frequency*), (Wikipedia; Web Page;*Vocal range*), (Pfeiler;Unpublished Work;*Akustik*; 2008.).

Every sound is made of several tones. This is the case also with vowels. Vowels are in fact sounds made of few formants. The formant with the lowest frequency is called f_1, the second f_2, and the third f_3. Most often the two first formants, f_1 and f_2, are enough to disambiguate the vowel.

The voiced speech of a typical adult male will have a fundamental frequency of from 85 to 155 Hz, and that of a typical adult female from 165 to 255 Hz.

Figure A- 10 Regions of formants f1, f2 and f3 illustrates what in fact formants are. They are regions of best heard tone. For every vowel the most important regions are tones made of formant 1 and formant 2.

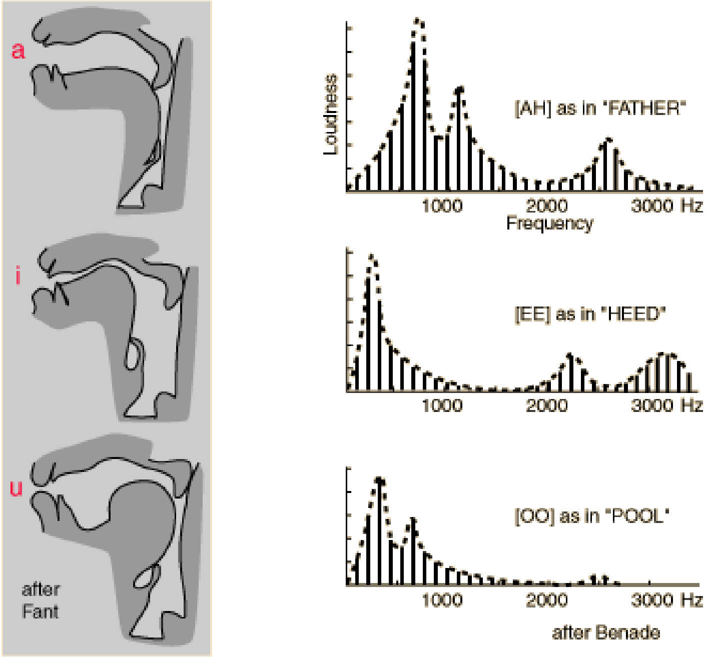


Figure A- 10 Regions of formants f1, f2 and f3.

(HyperPhysics by Georgia State University; Web Page;*Sound and Hearing*; 2005.)

Figure A- 11 Main formant region for vowels u, o, a, e and i shows what is the height of a tone when we pronounce these vowels.

Vowel formants	
Vowel	Main formant region
u	200–400 Hz
o	400–600 Hz
a	800–1200 Hz
e	400–600 and 2200–2600 Hz
i	200–400 and 3000–3500 Hz

Figure A- 11 Main formant region for vowels u, o, a, e and i.

(Wikipedia; Web Page;*Formant*)

Figure A- 12 Formant center is more detailed introspection into formants. It shows formant 1 and formant 2 frequency of peak point.

Vowel formant centers			
Vowel	IPA	Formant f_1	Formant f_2
u	u	320 Hz	800 Hz
o	o	500 Hz	1000 Hz
ɑ	ɑ	700 Hz	1150 Hz
a	a	1000 Hz	1400 Hz
ø	ø	500 Hz	1500 Hz
y	y	320 Hz	1650 Hz
æ	ɛ	700 Hz	1800 Hz
e	e	500 Hz	2300 Hz
i	i	320 Hz	2500 Hz

Figure A- 12 Formant center.
(Wikipedia; Web Page;*Formant*)

Nasal formants: 1500-2000 Hz.

In singing the frequency range is: between 65 and 1000 Hz.

Formants in singing: 2400-3200 Hz.

Also, there is the difference between formants in different languages and the pitch height or frequency range is different for different languages. This is why, for instance, Italian language is experienced as vibrant, live. It is pronounced in higher frequencies.

SECTION A 3 Frequency amplitude is sound pressure

See generally(Schmidt-Jones;Web Page;*Acoustics for Music Theory*; 2007.).

Amplitude is loudness. The size of a wave, how much it is "piled up" at the high points is its amplitude. Amplitude is in fact height of the wave. For sound waves, the bigger the amplitude, the louder the sound

Figure A- 13 Basic definitions of sound pressure displacement illustrates what are basic terms when speaking of sound pressure.

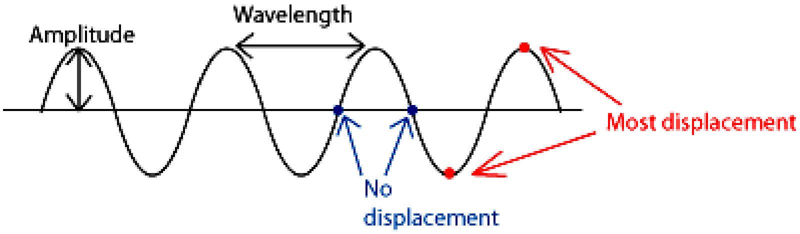


Figure A- 13 Basic definitions of sound pressure displacement.
(Schmidt-Jones;Web Page;*Acoustics for Music Theory*; 2007.)

Defining frequency of sound wave the oscillation of wave has been clarified researching density of oscillation.

Depending on the way the frequency range is made we talk about pitch of the sound.

The amplitude of the wave is a measure of the displacement: how big is the change from no displacement to the peak of a wave is. We measure the amplitude of sound waves in decibels.

Figure A- 14 Formation of Sound pressure level or dB shows the difference between amplitudes of softer and louder sound

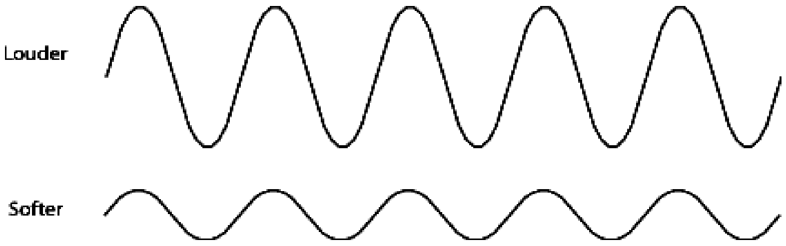


Figure A- 14 Formation of Sound pressure level or dB.
(Schmidt-Jones;Web Page;*Acoustics for Music Theory*; 2007.)

The term sound pressure and the other term sound pressure level are characteristics of sound wave directly correlated to wave length and are to be discussed. Terms Sound pressure and sound pressure level determinate sounds loudness that is defined with the height of the amplitude. Sound pressure is the change of atmospheric pressure , which is approximately 100 kPa, the change that can be heard by people are changes in pressure value of 20μPa = lower threshold of human hearing up to 20 Pa= upper threshold of human hearing. Pascal is value as follows 1 Pa = 1 N/m^2 = 10^{-5} bar = 9.8692×10^{-6} atm. Pascal can figurally be presented as a pressure of 10dkg onto an area of 1 m2.

Values of the sound pressure are dependent on frequency which in fact means that for the equal sound pressure result in low frequency much more energy should be used than for obtaining the same sound pressure result in higher frequencies. Also, each person is individually receptive to sound pressure and the threshold depends on person’s age.

A 3.1 How unit for loudness dB is introduced

See generally (Web Page;*Acoustics*).

The decibel is a logarithmic unit which is used in a number of scientific disciplines. In all cases it is used to compare some quantity with some reference value. Reference value in sound pressure is the smallest difference between two pressures that can be heard by humans. Usually the reference value is the smallest likely value of the quantity. Sometimes it can be an approximate average value.

In acoustics the decibel is most often used to compare sound pressure, in air, with a reference pressure. References for sound intensity, sound power and sound pressure in air are amongst others which are also commonly in use.

Decibel is a logarithm of a ratio.

Acousticians use the dB scale for the following reasons:

Quantities of interest often exhibit such huge ranges of variation that a dB scale is more convenient than a linear scale. For example, sound pressure radiated by a submarine may varies by eight orders (or decimals) of magnitude depending on direction.

The human ear interprets loudness on a scale much closer to a logarithmic scale than a linear scale.

Sound pressure level is very important characteristic of sound and the ultimate effect on listener is the loudness which is also called sound pressure level and is measured in dB.

Sound pressure is absolute term in physics of sound and sound pressure level is relative term and is much more useful in room acoustics because it describes the difference between the pressure of quite atmospheric pressure and relevant sound pressure that we would like to measure. Sound pressure is measured in laboratory conditions and is therefore not that useful for room acoustics. The relation between atmospheric pressure which is quiet and sound pressure level that is heard as a sound is correlated in logarithmical equation. $L_p=10\log\frac{p^2}{p_0^2}$ further $L_p=20\lg\frac{p}{p_0}$ (dB).

L_p=sound pressure level in dB.

p=measured sound pressure of concern.

p_0= starting sound pressure

The difference of pressure that human ear can detect is 2×10^{-5} N/m2 or 0, 00002 Pa. The upper human threshold value is p_0=20 μPa.

If in this equation values of upper and lower threshold are inserted then we will get that sound level pressure level in hearable field are from 0 to 130dB. L_p=10log $\frac{\left(2\times10^{-5}\right)^2}{\left(2\times10^{-5}\right)^2}$ further

$L_{p=}$20lg $\frac{2\times10^{-5}}{2\times10^{-5}}$ =L_p=0 dB. Lp=10log $\frac{20^2}{\left(2\times10^{-5}\right)^2}$ further $L_{p=}$20lg $\frac{20}{2\times10^{-5}}$ Lp=130 dB. So the range of 130 dB means that within hearable area human ear can detect 130 differences in sound pressure and each difference of 0.00002 Pa is heard as a difference of 1 dB.

When calculating levels of sound we will always use dB units, whether we are dealing with sound pressure levels or sound power levels or with sound intensity levels. Level is always going to be a derivate from smallest hearted difference.

Reference value: smallest pressure difference that can be heard (in air) = 0.00002 = 2x10^5 Pa

Reference value: smallest pressure difference that can be heard (in water) = 0.000001 = 1 x10^6 Pa

Reference value: smallest intensity difference that can be heard = 0.000000000001 = 1x10 $^{-12}$ W/m^2

Reference value: smallest power difference that can be heard = 0.000000000001 = 1x10 $^{-12}$ W

DB are always showing the proportion whether we are talking about pressure, intensity or power of sound (sound power level=is the energy or the power that is sent to air from the sound source. the sound source we use for the equation is ball of area 1m2, r is 0.28 m). The fact is that the equation for sound pressure and sound pressure level should be carefully clarified because on that principle other equations for power or intensity are derived. The factor 10 is exclusively related to the d in dB the scales in dB are in fact build-up and calculated in B (bels) but expressed in dB (decibels = 1/10 bel).

Therefore in acoustic formulas we find these repeatedly divisions and multiplications by 10 and it is toggling between the logarithmic calculation scale and the way bels are expressed as a convention in dB for pragmatic reasons. (Acoustics Forum; Web Page;*The dB scale & dBs: getting some feel*; 2008.)

A 3.2 Sound pressure level

See generally (Web Page;*Acoustics*).

When measuring all these levels we use conditions of frequency of 1000 Hz. Pressures are compared with exponents ^{2} , why?

The answer is because the power in a sound wave goes as the square of the pressure. Similarly, electrical power goes as the square of the voltage. The log of the square of x is just 2 log x, so this introduces a factor of 2 when we convert to decibels for pressures. For power of sound and sound intensity we would need only log x because it is in linear proportion, not in square proportions between two measures.

dB (SPL)

dB (Sound Pressure) — for sound in air and other gases, relative to 20 micropascals (μPa) = 2×10^{-5} Pa, the quietest difference between sound a human can hear. This is roughly the sound of a mosquito flying 3 meters away. This is often abbreviated to just "dB", which gives some the erroneous notion that "dB" is an absolute unit by itself. Since it expresses a ratio of two quantities with the same unit, it is a dimensionless unit. dB is not SI unit. It is a measure between two pressures, powers or intensities. A decibel is one tenth of a bel.

L_p=10log $\frac{p^2}{p_0^2}$ further $L_{p=}$20lg $\frac{p}{p_0}$ (dB). L_p=sound pressure level in dB. p=sound pressure being measured of concern. p_0= is the reference sound pressure.

If the pressure is doubled, the sound pressure level is increased with 6 dB. It is in fact 20 log 2.

In general in acoustics, levels of sound pressure, sound intensity and sound power are calculated in logarithmical manner. dB are units that are formed on logarithm base and therefore they can not be added directly. This is done as described in one of following titles.

SECTION A 4 Sound power, sound power level

See generally (Wikipedia; Web Page;*Sound power level*), (Wikipedia; Web Page;*Sound power*).

In acoustics we are often interested in strength of the sound source so that we could get dB out of that information. This is usually question when buying stereo system and the strength of that source. From this question we further definite values for strength of source that is independent on room's dimensions and the distance of listener, which is in other words dependent only on strength of source. The term is called Sound power level and is defined as sound energy that is emitted from the source to all directions in one second. The unit for it is Watt.

dB SWL

dB Sound Power Level — relative to 10^{-12} W.

$$L_w = 10 \text{x} \log_{10} \frac{W}{W_0} \text{ (dB)}$$

where W_0 is the 0 dB SWL reference level:

$W_0=10^{-12}$ W. W=measured power upper threshold is 1 W.

The sound power level is given the symbol L_W or SWL. This is not to be confused with dBW, which uses 1 W as a reference level.

(Sound power equation is $L_w=10 \log W/W_0$ (dB).

Very rarely is this equation for gaining dB out of sound power used. More often we want to know how to gain more dB and which is the factor of augmentation to get more levels of dB. As for relation between sound pressure and getting sound pressure level the same relation is established between sound strength and sound strength level to get result of changing in ranges of 1 dB which is the smallest hearable difference of level for human ear. For a change of 1 DB the sound energy change should be some 10^{-12} W. Sound intensity levels are also added in logarithmical scale, not in directional adding.

Figure A- 15 Examples of sound pressure levels shows the correlation between power in Watts and sound power level in dB.

Situation and sound source	sound power P_{ac} watts	sound power level L_w dB re 10^{-12} W
Rocket engine	1,000,000 W	180 dB
Turbojet engine	10,000 W	160 dB
Siren	1,000 W	150 dB
Heavy truck engine or loudspeaker rock concert	100 W	140 dB
Machine gun	10 W	130 dB
Jackhammer	1 W	120 dB
Excavator, trumpet	0.3 W	115 dB
Chain saw	0.1 W	110 dB
Loud speech	0.001 W	90 dB
Usual talking, Typewriter	10^{-5} W	70 dB
Refrigerator	10^{-7} W	50 dB
(Auditory threshold at 2.8 m)	10^{-10} W	20 dB
(Auditory threshold at 28 cm)	10^{-12} W	0 dB

Figure A- 15 Examples of sound pressure levels.

See (Wikipedia; Web Page;*Sound power*).

SECTION A 5 Sound intensity level

See generally (Wikipedia; Web Page;*Sound intensity level*), (Web Page;*Acoustics*), (Ono Sokki co, Japan; Web Page;*Technical Report Index*).

This may be defined as the rate of sound energy transmitted in a specified direction per unit area normal to the direction. With good hearing the range is from about 0.000000000001 Watt per square meter to about 1 Watt per square meter (12 orders of magnitude greater). The sound intensity level is found from intensity I (W/m^2) by:

Sound Intensity Level = 10 x lg $\frac{I}{I_0}$ dB

Note: 1x10^{-12} W/m^2 normally corresponds to a sound pressure of about 2 x 10 $^{-5}$ Pascal which is used as the datum acoustic pressure in air.

Sound intensity meters are becoming increasingly popular for determining the quantity and location of sound energy emission.

dB SIL

dB Sound Intensity Level — relative to 10$^{−12}$ W/m^2, which is roughly the threshold in air.

where I_1 and I_0 are the intensities.

The sound intensity level is given the letter "L_I" and is measured in "dB". dB is dimensionless.

If I_0 is the standard reference sound intensity and is 10^{-12} w per m2

(W = watt), then instead of "dB" we use "dB SIL". (SIL = sound intensity level). These units are not allowed by SI system of measurements but are here appropriate to describe more precisely on which relation does dB level relies on.

Sound intensity level is in fact sound power applied on specific area of 1 m2.

To hear a difference of 1 dB the power of energy should differ for 10 $^{-12}$ W per m2. That is then I_0

Lower threshold limit of human hearing is 10 $^{-12}$ W/m^2, and upper threshold limit of human hearing is 10 W/m^2.

We use sound intensity level for describing how the sound spread in an area.

A 5.1 The intensity in free sound field in open space

Every time the distance from a sound source is doubled the intensity of the sound reduces by a factor of four: I= Wsource/4πr2. There is an inverse square relationship between the sound intensity and the distance from the sound source.

Figure A- 16 Inverse square law says that with distance doubling the sound power level SPL decreases for -6 dB.

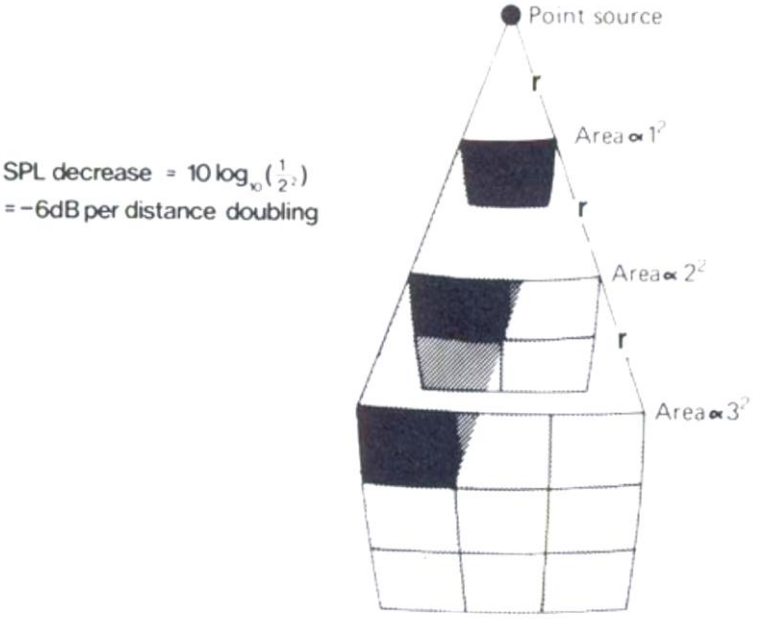


Figure A- 16 Inverse square law says that with distance doubling the sound power level SPL decreases for -6 dB.
(Decimin Control Systems P. Ltd. ; Web Page;*Technical information*)

The area of a sphere = 4 x π x r2

Sound intensity is defined as the power per unit area. (Feilding;Web Page;*Lectures 001-013*). Therefore the sound intensity as a function of distance from a source is expressed as:

I = Wsource /Asphere = Wsource/4πr2

where

I = the intensity of the sound (in Wm-2)

Wsource = the power of the source (in W)

r = the distance from the source (in m)

An example of concrete usage of calculating levels:

A loudspeaker radiates (W_{source})100 mW. Calculate the sound intensity level (SIL) at a distance of (r)2 m from the loudspeaker when it is mounted on (Q)1, 2 and 3 boundaries $W_{reference}$ is 10^{-12} W

Calculation of Sound intensity level at some distance with 1,2,3 boundaries:

$SIL = 10 \log_{10} (W_{source} / W_{reference}) + 10 \log_{10}(Q) - 10 \log_{10}(4\pi) - 20 \log_{10}(r)$

The presence of 1, 2 and 3 boundaries reduces the sphere to a hemisphere, half hemisphere and quarter hemisphere, which corresponds to a Q of 2,4 and 8, respectively.

Figure A- 17 directivity patterns.

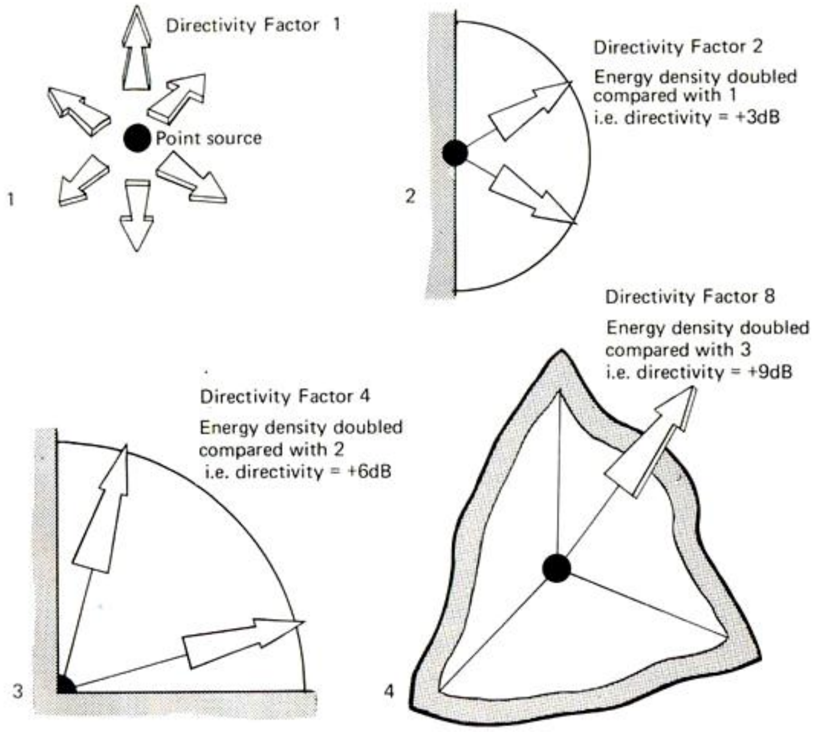


Figure A- 17 directivity patterns.

(Decimin Control Systems P. Ltd. ; Web Page;*Technical information*)

SECTION A 6 Correlation between sound pressure, sound power and sound intensity

Conclusion: the term sound pressure level is most general term because it deals with basic characteristic of sound wave and it is pressure, after that we introduced sound power . Sound power is used because it describes the relationship between the source energy and sound level, after that third term is introduced and is called sound intensity. It is significant because it describes the relation between source energy on specific area and sound level.

Figure A- 18 dB correlated to pressure ratio, energy ratio and effective pressure and intensity values is very illustrative because it shows on a glance the ralations between dB and some exact values; like sound pressure in Pa ; sound intensity that is the same value as sound power in W/m2 but with different unit W. Also it shows the correlation between dB and some important ratios which are; energy ratio; sound pressure ratio.

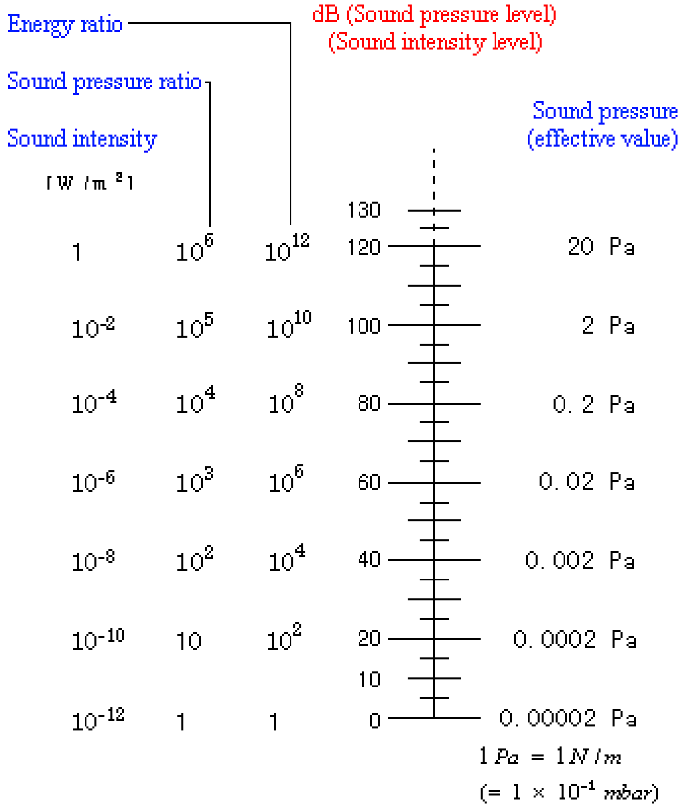


Figure A- 18 dB correlated to pressure ratio, energy ratio and effective pressure and intensity values.
(Ono Sokki co, Japan; Web Page;*Technical Report Index*)

SECTION A 7 Sound levels addition

A 7.1 Logarithms in acoustics

See generally (University of Colorado; Web Page;*Logarithms: Definition and the Basic Logarithms*).

Term of sound level is based on calculating in logarithmical range of operations. Why do we use logarithms in the field of sound waves and what in fact are logarithms?

Common reaction for most architects when meeting logarithms is the total rejection of the whole theme of physical characteristics of sound. The rejection happens because they are meeting with term of logarithm. Because of that rejection, it is very useful to demystificate the term logarithm because of further easier understanding of basic characteristics of sound wave particles.

Logarithms are - at the most basic level - invented to answer the more general question of how does one extract the base or exponent of an algebraic power when one of these is an unknown.

Logarithm is in fact is the way to scribe down the inversion of exponentiation. Inversion of exponentiation is usually done with rooting, but can also be written in logarithm form because it suites us better this way.

Namely, logarithms are used when we are dealing with too large numbers to comprehend them, for instance in astronomy, or in calculating pressures in our case that are superponated on value of atmospheric pressure that is constant.

With logarithm we ask ourselves how many times should we potent base of 10 to get nummber1000. In mathematical language we would put down this question in this way:

$10^x = 1{,}000$

$\mathrm{Log}10^x = \mathrm{Log}1{,}000$

$\mathrm{Log}10^x = x$.

Why do we use logarithms?

The question is: what is x in the above formula? How do we solve for x? We invent an operation called the logarithm - abbreviated as Log - and we apply this operation to both sides of the above relation.

Why do we use logarithms in acoustics?

When looking into equations for instance of sound pressure, the part of equation is log $\frac{p}{p_0}$, which is in fact abbreviation of equation $\log_{10} \frac{p}{p_0}$ (read logarithm on base 10). Logarithms on base 10 are those that are used in acoustics. Logarithms are in acoustics used to abbreviate lots of decimal places and there for we use log on base 10.

In fact, we are dealing with the ratio between two which is in mathematical language written as ratio or/ of the referent position of the pressure and some other pressure. Referent value in sound pressure is the smallest difference that we can hear between two pressures. We are in the field of pressures and are looking at pressures relations in Earth condition and that is a constant (even though it is not a constant because it changes every day with whether conditions, but for mathematical purpose it is constant), and that is 1 atmosphere. Every pressure change is according to that superponated with atmosphere pressure. Because the atmosphere pressure is expressed as unit 1 Pa = 1 N/m^2 = 10^{-5} bar = 9.8692×10^{-6} atm in this term we see 10 with exponency -6. Logarithm is mathematical invention created to neglect those numerous decimal places as for instance in case of pressure and atmosphere unit, or in astronomy distances between planets. The conclusion is that logarithm is mathematical invention how to deal with huge values and tremendous range without using them directly but rather compare their relations. In case of sound acoustics, we use logarithms to avoid using 6 decimals in relation of sound pressure that is heard as a minimal difference and some other pressure with upper threshold for pain of 20 Pa.

A 7.2 Basic logarithmic rules

See generally (Acoustics Forum; Web Page;*The dB scale & dBs: getting some feel*; 2008.), (Web Page;*Acoustics*).

Logarithmic operators lower 1 level compared to Arithmetic operators.

An arithmetic power becomes a logarithmic multiplication:
$10x\log(6^2) = (10x\log(6))x2 = 10x2x\log(6) = 20x\log(6)$

An arithmetic root becomes a logarithmic division:
$10x\log(\sqrt{}(6)) = \frac{10x\log 6}{2} = \frac{10}{2}x\log(6) = 5x\log(6)$

An arithmetic multiplication becomes a logarithmic addition:
$10x\log(6x2) = 10x\log(6) + 10x\log(2)$
When you calculate energetically, ignoring phase relationship (hence uncorrelated signals):
If you have 14 sources of 74.5 dB or if you increase a level with a factor 14 then:
L_p = 74.5 dBx14 = 74.5 + 10xlog(14) = 74.5 + 11.5 dB = 86 dB

An arithmetic division becomes a logarithmic subtraction:

$10x\log\frac{6}{2} = 10x\log(6) - 10x\log(2)$

When you calculate energetically, ignoring phase relationship (hence uncorrelated signals)
If you want to divide the number of radiating sources by 5 or decreasing your level with a factor 5 then:
Lp = $\frac{74.5dB}{5}$ = 74.5 - 10xlog(5) = 74.5 - 7.0 dB = 67.5 dB
This is in fact equal to following multiplication:
74.5 dB at 20% = 74.5 x 0.2 = 74.5 + 10xlog(0.2) = 74.5 + -7.0dB = 74.5 - 7 dB = 67.5 dB

An arithmetic addition becomes a logarithmic.. what? There is no lower level operator available

In order to add dB values you must first convert them to the arithmetic equivalent of the bel (not dB) value, then adding, then converting the resulting sum back to the equivalent logarithmic dB value.

Let's add 74.5 dB + 83.2 dB:

The antilog (arithmetic equivalent) of a dB value of 74.5 dB is 10^(74.5/10) where the (74.5/10) is the conversion from dB to bels. The 1st 10 is the base of the logarithmic scale.

Lp = 74.5 dB + 83.2 dB = 10*log(10^(74.5/10) + 10^(83.2/10)) = 10*log(28,183,829 + 208,929,613) = 10*log(237,113,442) = 83.7 dB

An arithmetic subtraction becomes a logarithmic…what? Again, there is no lower level operator available.One cannot directly subtract dB values.

If you somewhere see dB values being subtracted, that operation shows an arithmetic division with a factor > 1 or > 100% OR a multiplication with a factor >0 and <1.

An amplifier set to -30 dB means that the amplifier is set to 10^(-30/10) = 0.001 = 0.1% of its nominal output.

This minus dB scale is nothing else than a logarithmic, in dB expressed, percentage versus the nominal maximum of 100%.

The solution for a subtraction is the comparable with the above addition. A roundabout via the arithmetic equivalents (antilogs) of the bel (not dB) values is required.

The only difference is that the addition + operator is substituted by the subtraction - operator.

Example:

Remove 1 sound source of 79.3 dB from a room with 5 sources totalling 84.8 dB (number of sources doesn't matter, the total level at the measurement point is defining)

Again this is an energetic calculation, not taking phase influence into account (uncorrelated sound)

84.8 dB - 79.3 dB = 10*log(10^(84.8/10)-10^(79.3/10)) = 10*log(301,995,172-85,113,804) = 10*log(216,881,368) = 83.4 dB

Note: if the 2nd term is equal or larger than the 1st term resulting in a 0 or negative arithmetic value the calculation will return an error for the same simple fact that logarithms just can't work with, or express 0 or negative values in the arithmetic sense of the concepts.

One just cannot express in dB that there is no sound and you certainly cannot express negative sound in dB.

Sound energy levels in decibels from independent sources may not be added directly. The sound pressure levels must be converted back to arithmetic units and added and then reconverted to decibel units. The nomogram is used for easily adding two sound levels together.

If there are two sound sources in a room - for example a radio producing an average sound level of 62.0 dB, and a television producing a sound level of 73.0 dB - then the total sound level is a logarithmic sum according to following formula:

$$L_\Sigma = 10 \cdot \log_{10}\left(10^{\frac{L_1}{10}} + 10^{\frac{L_2}{10}} + \cdots + 10^{\frac{L_n}{10}}\right)\ \mathrm{dB}$$

L_Σ = Total level and L_1, L_2, ... L_n = sound pressure level of the separate sources in dBSPL Combined

sound level = $10 \times \log_{10}\left(10^{\frac{62}{10}} + 10^{\frac{73}{10}}\right)$

= 73.3 dB

The equation for adding sources of the same level is:

$L_{ges}= L_i + 10 \lg n$ (dB)

n number of same sound sources

The same procedure is with adding sound intensity levels Li. This formula is used for adding Sound pressure level, sound power level and sound intensity level.

It could be noticed that total sound level is dependent on the ratio between the number of people singing in a choire.

And the following formula is going to be used when adding different sound source levels by using nomogram.

$L_{ges}= L_1+\delta L$

$\delta L= L_1-L_2$

Figure A- 19 Nomograph for combining two sound sources in decibels is used for easy commbining dB. In the example shown, two sound sources produce levels of 50 and 54 dB,respectively. What level would be produced with both sources operating together Delt or difference, 54-50=4 dB;amount to be added to higher level is derived from this nomogram and it is 1.5 dB. Final result with both sources operating is: 54+1.5=55.5 dB

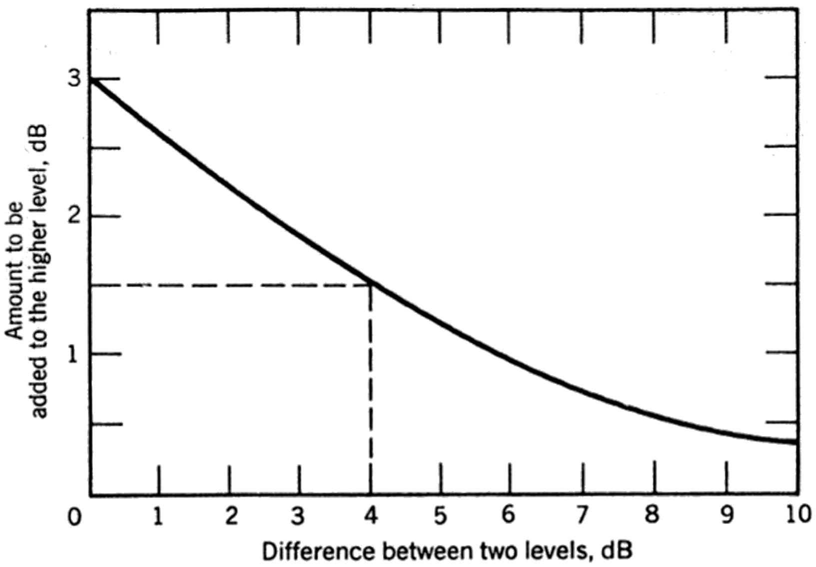
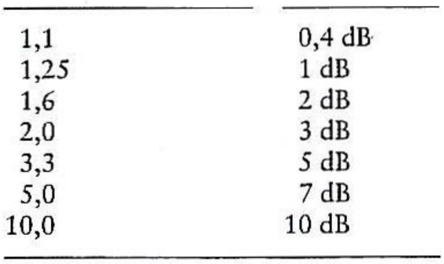


Figure A- 19 Nomograph for combining two sound sources in decibels.

(Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999)

A nomogram, nomograph, or abac is a graphical calculating device, a two-dimensional diagram designed to allow the approximate graphical computation of a function. The word nomograph is used when we want to illustrate the nomogram in graphical way. (Wikipedia; Web Page;*Nomogram*)

If we want to know the result of sound level based on the factor of augmentation then we can use the following Figure A- 20 Relation between the factor of augmnentation of sound power and sound level.



1,1	0,4 dB
1,25	1 dB
1,6	2 dB
2,0	3 dB
3,3	5 dB
5,0	7 dB
10,0	10 dB

Figure A- 20 Relation between the factor of augmnentation of sound power and sound level (Meyer;Book;*Kirchenakustik*; 2003)

.In the end of the table it should be said that the number of people that are singing in a choire is not that relevant as the factor of augmentation that they produce. In exploring the factor of augmentation the number of sources is not important, but in defining the exact level of the sound the number of sources is relevant in equations. Combining $L_{tot}= L_i + 10 \lg n$ (dB) and this table we can say $L_{tot\ 2}= L_{tot} +$ gain in sound level that can be read from the table as a factor that the choire should sound stronger. (Meyer;Book;*Kirchenakustik*; 2003)

The change of 1 dB is detectable only in laboratory conditions and is a change represented by hearing a mosquito flying 3 m in front of us. A change of 3 dB, which is actually doubling the sound energy level, would be just perceptible in room conditions. The change of 10 DB we hear as doubling of loudness or halving.20 dB is four times louder than the original sound.

This characteristics must be borne in mind when working in practice where gaining of 1 or 2 dB really does not mean a thing. We should then evaluate the gain we get and the effort that should be spent for such a minor change.

Figure A- 21 Subjective meaning of dB change level shows how in real conditions we hear differences between decibels.

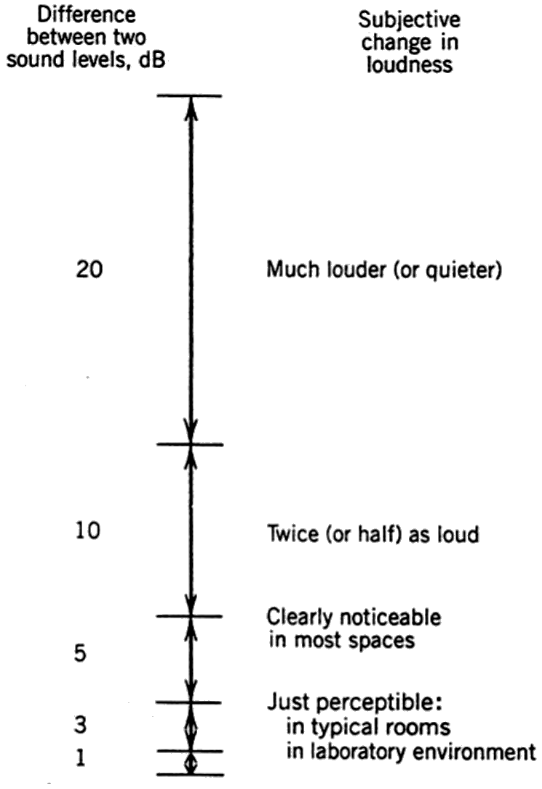


Figure A- 21 Subjective meaning of dB change level.

(Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999)

A 7.3 Superposition of sound waves

See generally (Feilding;Web Page;*Lectures 001-013*).

Note: for two different sounds, the combined level cannot be more than 3 dB above the higher of the two sound levels. However, if the sounds are phase related there can be up to a 6dB increase in SPL Sound pressure level like for instance in stereo sound system.

Figure A- 22 Adding sound waves can result with doubled sound level or can totally cancel the sound level

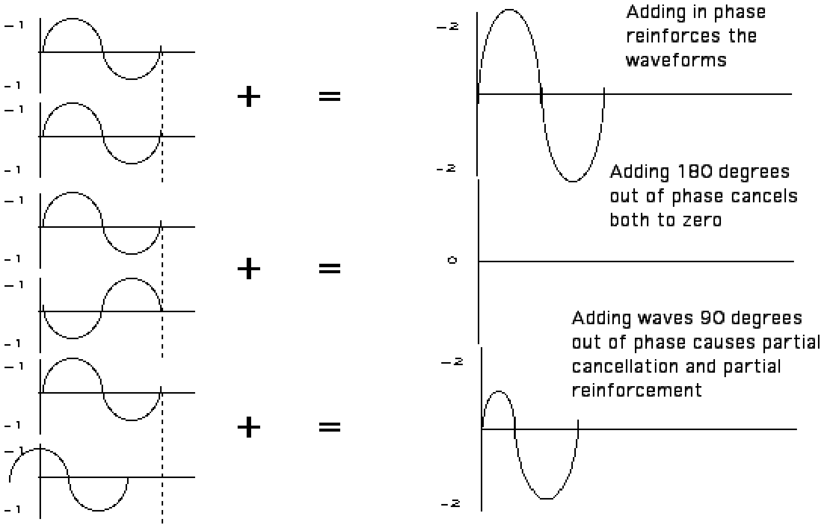


Figure A- 22 Adding sound waves can result with doubled sound level or can totally cancel the sound level.
(Feilding;Web Page;*Lectures 001-013*)

Phase alignment: when correlated sounds are added the result depends on their phase alignment.

Sounds which are aligned will add.

Sounds which are not aligned will cancel each other out at 180°

At other angles they will combine destructively to some degree.

When uncorrelated sounds add: Adding uncorrelated sounds of equal volume you get a 3 dB increase for every source you add.

Adding uncorrelated sounds of unequal volume dB have to be converted back to ratios before they are added together. This is because adding levels is done by logarithmical scale.

The level when uncorrelated sounds add:If sound waves are uncorrelated they do not add algebraically. Instead we must add the powers of the individual waves together. The power of a waveform is proportional to the square of the pressure levels so we must square the pressure amplitudes before adding them together. If we want the result as pressure we must take the square root of the result.

$$P_{\text{total uncorrelated}} = \sqrt{\;}\,(P_1^2 + P_2^2 + \ldots. P_n^2)$$

When correlated sounds are added the result may be louder or softer, when uncorrelated sounds add the result is always louder.

The reason for uncorrelated sounds to be always louder is because in this case the sound is projected from multiple sources.

It is not dependant upon their relative phases.

Level increase is not double because we are adding powers not pressures

Maximum possible level gain when two equal uncorrelated sounds are added is $P\sqrt{\;}\;2 = 1.414$.

In all these formulas with P it is to be aware that this pressure should be related with reference pressure in logarithmical manner t get dB levels out of them.

Air, for example impurities and water molecules, or smog and humidity are extra sources of absorption and have more effect at high frequencies and, as a result sound not only gets quieter, but also gets duller, as one moves away from a source, due to the extra attenuation these cause at high frequencies. The amount of excess attenuation is dependent on the level of impurities and humidity and is therefore variable.

SECTION A 8 Correlation between levels and frequencies

See generally (Web Page;Acoustics).

Loudness, a subjective measure, is often confused with objective measures of sound pressure such as decibels or sound intensity. Filters such as A-weighting attempt to adjust sound measurements to correspond to loudness as perceived by the average human. However, true perceived loudness varies from person to person.

The A Weighting curve is a graph that is used to 'weight' measured values of sound level where a specific set of weighting curves known as A, B, C and D weighting are often used. (Wikipedia; Web Page;*Weighting curve*).Measurements of sound intensity do not correspond to perceived loudness because the human ear is less sensitive at low and high frequencies, with the effect more pronounced at lower sound intensities. The four curves are applied to the measured intensity, for example by the use of a weighting filter in a sound level meter, to arrive at readings of loudness in phons or in decibels (dB), especially A-weighting). So, the most used weighting curve in acoustics is the A-weighting curve.

Loudness is measured in sones and loudness level is expressed in phons.

Loudness is the impression of the strength of a sound as perceived by a human listener. The loudness of a noise does not necessarily correlate with its sound level. The loudness level of any sound, in phons, is 1 decibel level of an equally loud 1kHz tone, heard binaurally by an otologically normal listener. Historically, it was with a little reluctance that a simple frequency weighting "sound level meter" was accepted as giving a satisfactory approximation to loudness. The ear senses noise on a different basis than simple energy summation, and this can lead to discrepancy between the loudness of certain repetitive sounds and their sound level.

The phon was proposed as a unit of perceived loudness level L_N for pure tones[1] by S. S. Stevens. (Absoluteastronomy; Web Page;*Phon*).The purpose of the phon scale is to compensate for the effect of frequency on the perceived loudness of tones. The phon model can be extended with a time-varying transient model which accounts for "turn-on" (initial transient) and long-term, listener effects. That is why phons are not part of the SI units system. This time-varying behavior is the result of psychological and physiological audio processing. The equal-loudness contours on which the phon is based apply only to the perception of pure steady tones.

All terms sound pressure, sound power and sound intensity are measured in 1000 Hz conditions.Equal loudness contours are called also phonlines and are in fact lines of the same loudness. Phonlines represent the same loudness level L_N at different frequencies from 16 Hz to 20kHz.

Figure A- 23 Equal loudness contour illustrated shows loudness measured in phons. The horizontal axis shows frequency in Hz.

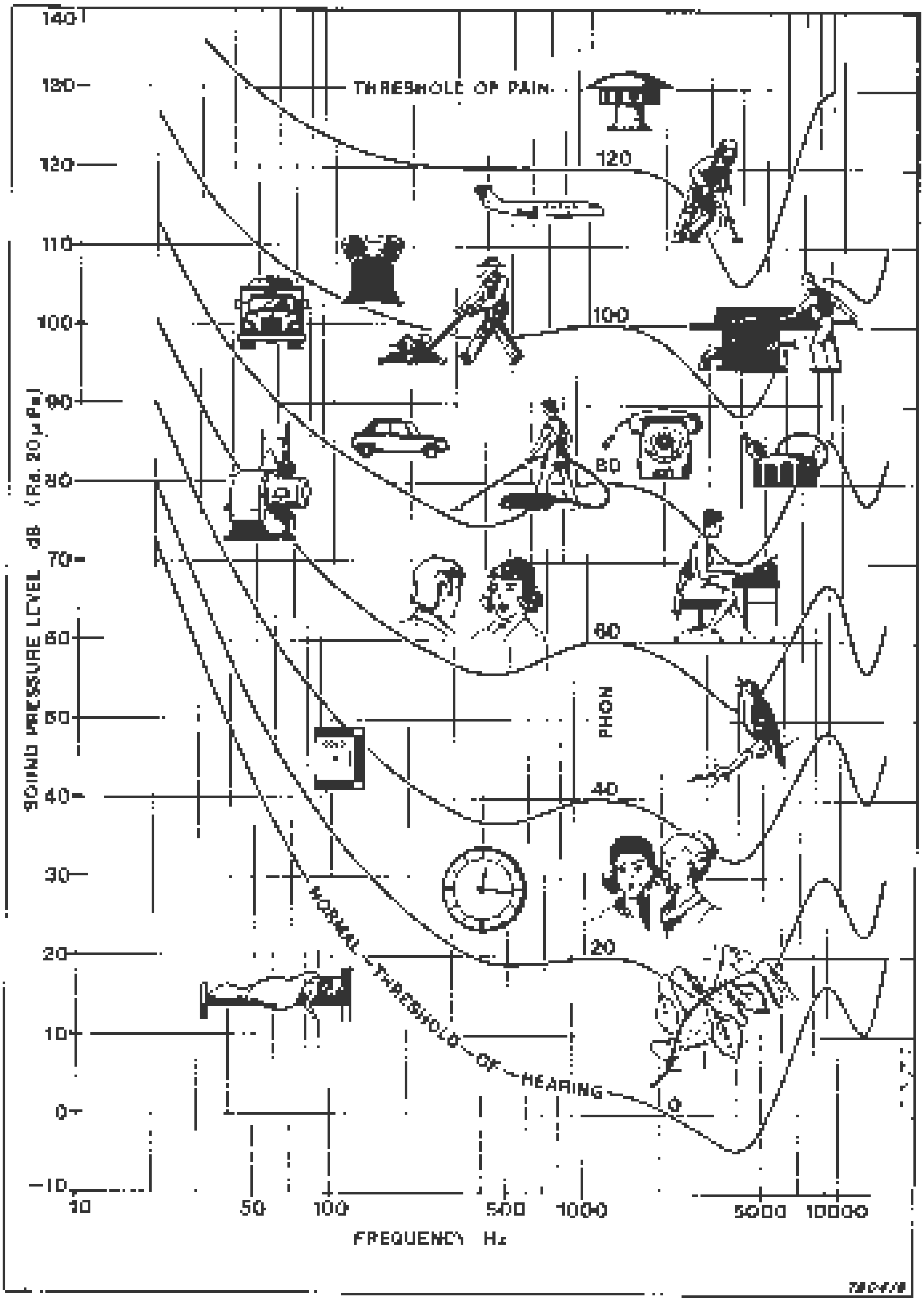


Figure A- 23 Equal loudness contour illustrated.

(LEARN London Metropolitan University; Web Page;*Equal loudness contours*)

Figure A- 24 Equal loudness contours from ISO 226:2003 revision in red color is in fact the same figure as Figure A- 23 Equal loudness contour illustrated but more recent and more up to date because it is drawn from ISO standards.

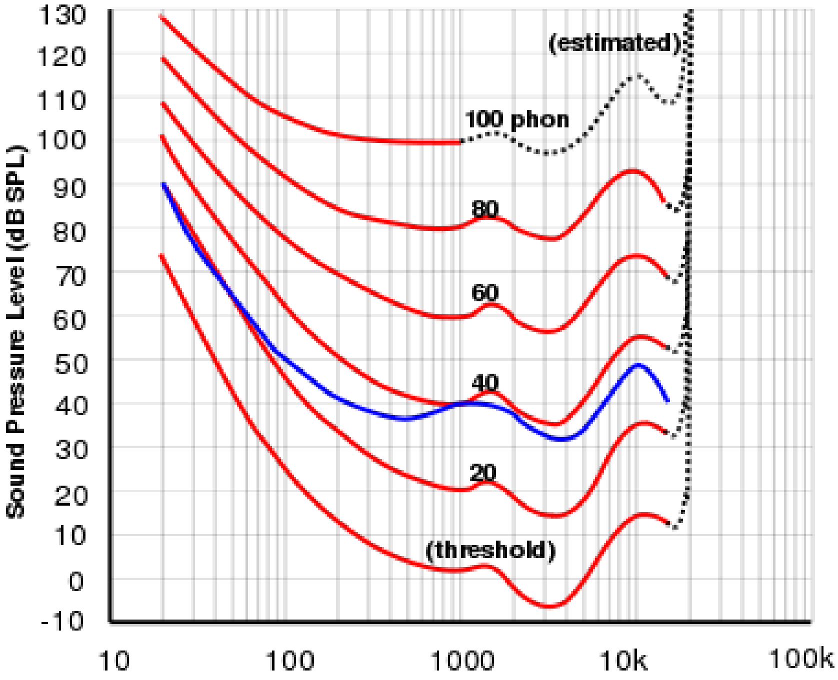


Figure A- 24 Equal loudness contours from ISO 226:2003 revision in red color. (Wikipedia; Web Page;*Equal-loudness contour*)

The sone was proposed as a unit of perceived loudness by S. Smith Stevens in 1936. In acoustics, loudness is the subjective perception of sound pressure. Although defined by Stevens as a unit, it is not one of the SI units According to Stevens' definition, the sone is equivalent to 40 phons, which is defined as the loudness level NL of a 1 kHz tone at 40 dB SPL The sone is a unit of comparative loudness with 0.5 sone=30 phons, 1 sone=40 phons, 2 sones=50 phons, 4 sones = 60 phons etc. The sone is inappropriate at very low and high sound levels where subjective perception does not follow the 10dB rule.

Loudness level calculations take account of "masking" - the process by which the audibility of one sound is reduced due to the presence of another at a close frequency. The redundancy principles of masking are applied in digital audio broadcasting (DAB), leading to a considerable saving in bandwidth with no perceptible loss in quality.

The sone is a loudness unit. Loudness is a subjective characteristic of a sound (as opposed to the sound-pressure level in decibels, which is objective and directly measurable). (Britanica; Web Page;*sone, phon*). Consequently, the sone scale of loudness is based on data obtained from subjects who were asked to judge the loudness of pure tones and noise. One sone is arbitrarily set equal to the loudness of a 1,000-Hertz tone at a sound level of 40 decibels above the standard reference level (i.e., the minimum audible threshold). A sound with a loudness of four sones is one that listeners perceive to be four times as loud as the reference sound.

A 10dB sound level increase is considered to be about twice as loud in many cases.

Figure A- 25 Sones and phons correlation is in fact a nomogram of real relations between these two values.

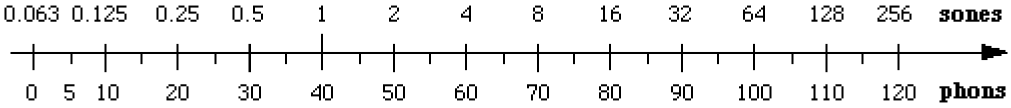


Figure A- 25 Sones and phons correlation.

(Wolfe;Web Page;*School of Physics*; 2004.)

SECTION A 9 Conclusion to Part A

The question about the possibility of developing methods for building superior sound spaces in this section only was explored according to the fundaments of contemporary methods.

All of these fundament elements of sound led us to the term of sound level in a general sense. It is shown that we can use the term sound level by itself because the level is always a logarithmical relation of two measured values of the same kind. So, we measure sound pressure,power or intensity and the result is sound level in dB.

Part A showed that the sound level is dependent on frequencies.

Also, sound levels are added in a logarithmical manner and therefore our sense of the perception of the augmentation of sound is not linear but logarithmical. In a real application the sound should be augmented by 10 dB for we cannot notice the difference in the doubling of the level. It is very important that the sound of 1 dB is only the sound of a mosquito flying 3 meters from the listener. It is important further to acoustical science to be aware that improving a sound value by 2 dB really does not mean that much of a gain.

It also should be pointed out that one-third of the total power of a 75-piece orchestra comes from the bass drum. Also for better understanding it should be said that the uppermost octave of the piccolo is 2,048-4,096 Hz. High frequency sounds of 2-4,000 Hz are the most damaging to the hearing.

PART B Room acoustics

SECTION B 1 Basic definitions of room acoustics

See generally (Wikobooks; Web Page;*Microphone technique*), (Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.).

This section is exploring basic definitions of room acoustics and these are: direct sound, reverberation, reflection and absorption. The research starts with some basic definitions.
We distinguish direct and reverberant sound.

1) Free sound field is the sound field that happens in open space; the sound level decreases as the distance between the performer and the auditor is augmented. The distance between the interpreter and the auditor has an influence on sound level but in this calculation reflection also contributes a great deal. The term performer is used because in this dissertation the focus is not on general acoustics but the specific acoustics obtaining in structures designed for such events as concerts, recitals and theatrical performances
2) Direct sound is only one wave coming from the source into open space forming a free field in which the wave is expended.
3) Reverberant sound is the sound formed of numerous sound waves in an enclosed space, or room. A reverberant field is formed in enclosed rooms and a free field is formed in open space.

Figure B- 1 Three parts of impulse response of the room: direct sound, early reflection and reverberationillustrates tree major parts of sound. These parts are: direct sound, early reflection and reverberation.

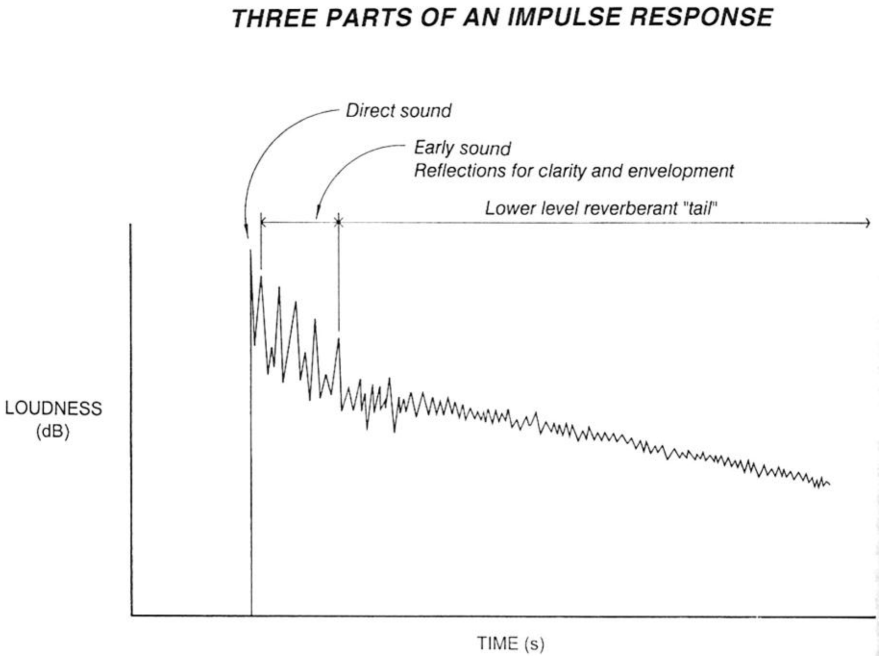


Figure B- 1 Three parts of impulse response of the room: direct sound, early reflection and reverberation.
(Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999)

It is important to understand how sound propagates due to the nature of the acoustic environment .There are four basic ways that this occurs:

1) Reflection. Sound waves are reflected by surfaces if the structure is as large as the wavelength of the sound. Reflection is the cause of echo (simple delay), reverberation (many reflections cause the sound to continue after the source has stopped), and standing waves (the distance between two parallel walls is such that the original and reflected waves in phase reinforce one another and as a result we get spots of no sound at all).

2) Absorption .Sound waves are absorbed by materials rather than reflected. This can have both positive and negative effects depending on whether you desire to reduce reverberation or retain a live sound.

3) Diffraction .Objects that may be between sound sources and microphones must be considered due to diffraction. Sound will be stopped by obstacles that are larger than its wavelength. Therefore, higher frequencies will be blocked more easily than lower frequencies.

4) Refraction .Sound waves bend as they pass through media with varying densities. Wind or temperature changes can cause sound to seem as if it were literally moving in a different direction than expected.

5) Diffusion is the efficacy by which sound energy is spread evenly in a given environment. A perfectly diffusive sound space is one that has certain key acoustic properties which are the same anywhere in the space.

In a diffuse sound field, with the exception of low rooms (which are spaces with a great floor area but which are small in height) equality of sound level is obtained in every sitting place, ideally. In room acoustics, the goal is to make sure that all auditors hear the same sound characteristics; it is an ideal case which we should asymptotically aim at reaching.

Figure B- 2 Formatting a diffuse sound field illustrates how in fact a diffusive field is different from the outdoor or free field behaviour and indoor or reverberant field behaviour.

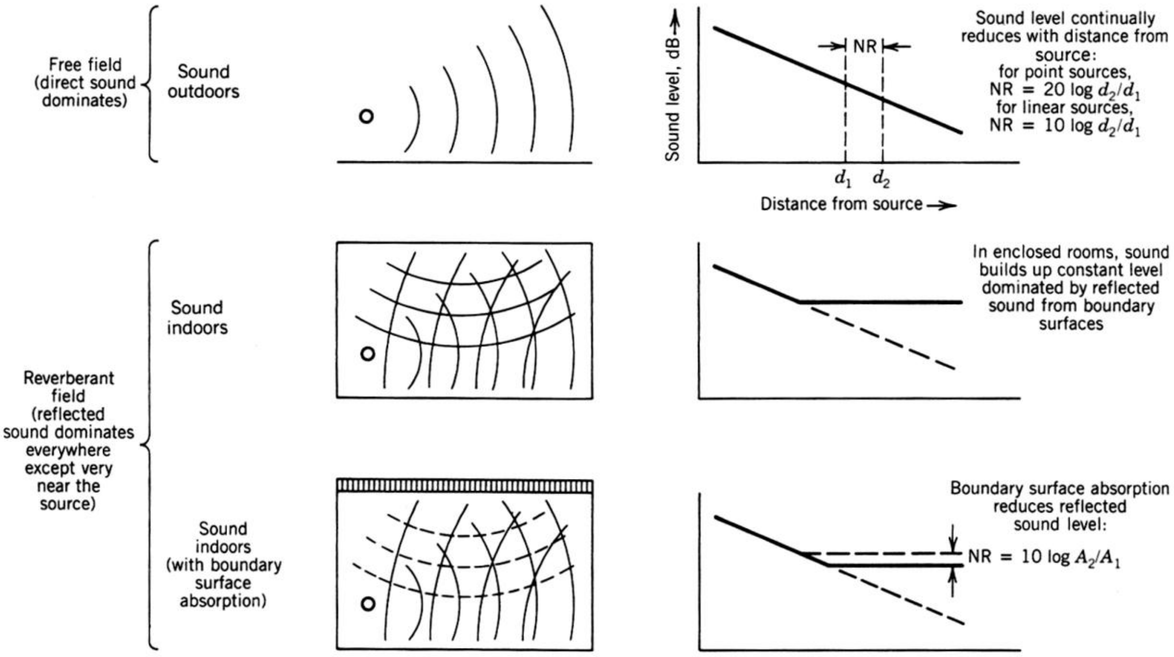


Figure B- 2 Formatting a diffuse sound field

(Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999)

The equation for intensity in open space has been given in previous chapters. Here a summary of that chapter's content is given through the equation for the intensity in a free sound field in open space.

Sound pressure level in open space can be calculated as follows:

$$Lp=Lw - 20 \log \frac{r}{r_0} -11 \text{ dB} + D$$

Lw sound power level of sound source

r.... distance of the auditor from the source

r0.....the beginning value 1 m

D.... directivity index in dB is derived from directivity factor, which is the part of the former chapter discussing the superposition of sound waves, together with the attached figure.

In general, this formula means that doubling the distance from the source will decrease the sound level by 6 dB, and that with a further distancing from the source by10 times the decrease will be 20 dB.

Direct sound is the first sound a listener hears coming from an instrument on the stage - that is, the sound that travels directly from instrument to listener. Direct sound constitutes only 1 percent of the sound that can be heard in a hall. (Noxon;Web Page;*Auditorium Acoustics 101,102,103,104*; 2002)

The remaining 99% of the sound is indirect sound that consists of early reflected sound and reverberant sound. To define it differently, only 1 ray is a direct ray and the additional 99 rays are reflections of that one. The term early sound encompasses the direct sound plus all the reflections that reach a listener s ear in the first 80 milliseconds. Reverberant sound indicates all the reflections that arrive after 80 ms. Here it should be pointed out that the borderline for speech is 50 ms and for music

80 ms. Frequently these references apply to the ratio of the energy in the early sound to that in the reverberant sound. After a specific time direct sound is reflected, the first reflected being the early lateral reflections, which are in fact the first reflections from the side walls and ceiling. These first reflections reinforce direct sound experience. After this time of 80 ms other reflected sound will be used in forming reverberations. Consequently, the less absorbent material the longer duration of the sound wave will be. Until the difference between the initial sound level and the measured sound level is smaller than 60 db the reflections are going to contribute to reverberation. The greater the reverberation, the greater is the reverberation field energy measured. The sound emitter, or for instance loudspeakers, should produce a sound level at about 65 dB, everywhere in the seating area, to provide a diffuse sound field. A diffusive sound field is a type of sound energy diffusion where the sound pressure is equal in every place of the room and reflections of sound waves are equally probable in each direction, in every area. The diffuse sound field is the most wanted part of the reverberant field.

The acoustics are the best when uniform at every sitting place, and this means that a diffusive sound field has been established. The natural noise floor of the hall should be at least 20 to 30 dB quieter than the sound level during performance.

Late reflections are an unwanted part of the sound because they come across as echo. An explanation about late reflection is given in one of the following chapters in the section entitled other room acoustic characteristics.

B 1.1 Reverberation time (RT60)

Today, the calculation of reverberation time should be viewed as an important check on the acoustical design of the hall, rather than the basis of design.

Reverberation time (RT) is a phenomenon that appears when the sound is weakening. This is the duration of sound until it diminishes, but only the time duration when the difference between initial and diminished sound is 60 dB or more.

Figure B- 3 Definition of reverberation time illustrates upper definition of reverberation

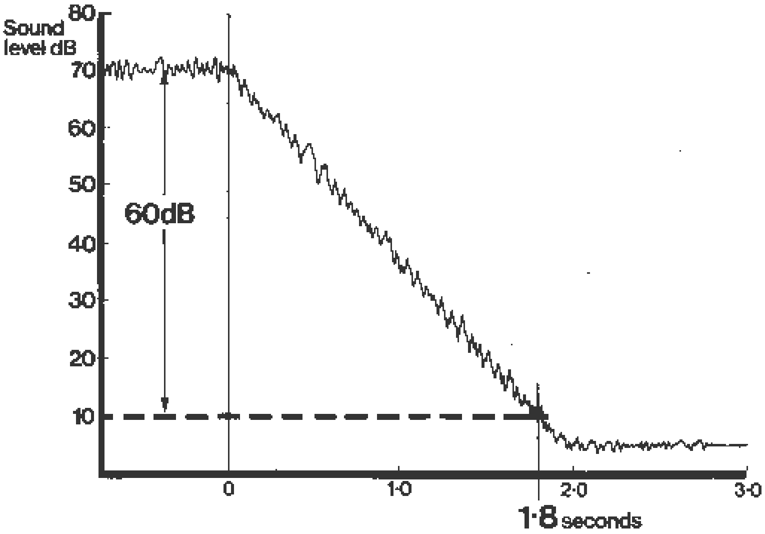


Figure B- 3 Definition of reverberation time

In room acoustics that reverberation time depends on sound reflection and the volume of the space. Harvard University professor Wallace Clement Sabine (1868 - 1919) was the first person to work scientifically with acoustics and he invented the Sabine formula for reverberation, as follows:

$$T=\frac{55{,}3\times V}{A\times c_0}=0{,}163\ \frac{V}{A}\ \text{(s)}.$$

V… is the volume of the space m^3.

A… is the sum of all absorption grades of materials in the space in m^2

c_0... sound velocity in air= cca 340 m/s

This formula in fact means that reverberation time is growing, in other words, is proportionally dependent on the enlargement of the space volume, and is reversible proportional with the absorption in space. After long-lasting observations of reverberation and its relations to the volume of the space, optimal values were found. In practice, the toleration of deviation from these optimal values is relatively wide, on average 20%.

Figure B- 4 Reverberation tolerance range for optimal reverberation for music shows in graphical form the tolerance of about 20 percent for music, and Figure B- 5 Reverberation tolerance range for optimal reverberation for speech, communication and music rehearsal shows that tolerance generally for speech

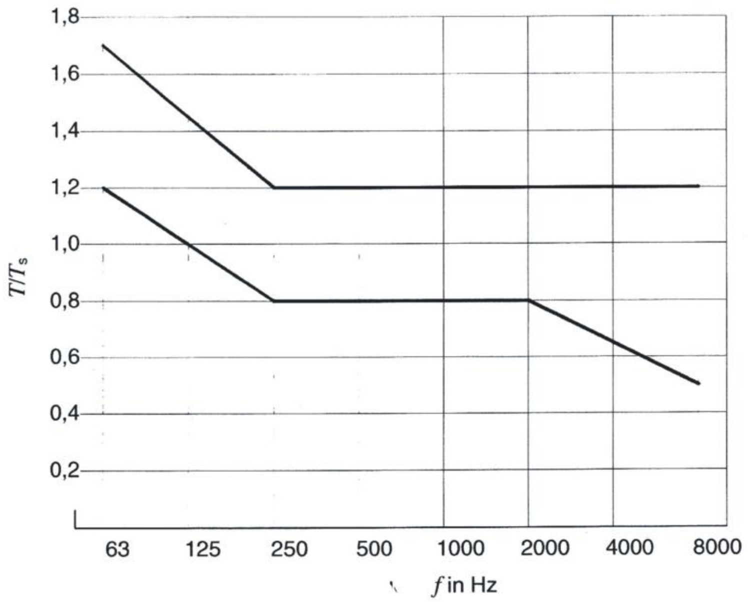


Figure B- 4 Reverberation tolerance range for optimal reverberation for music
(ÖNORM; Government Document;*ÖNORM B 8115-1,2,3,4,5*; 2003-09-01)

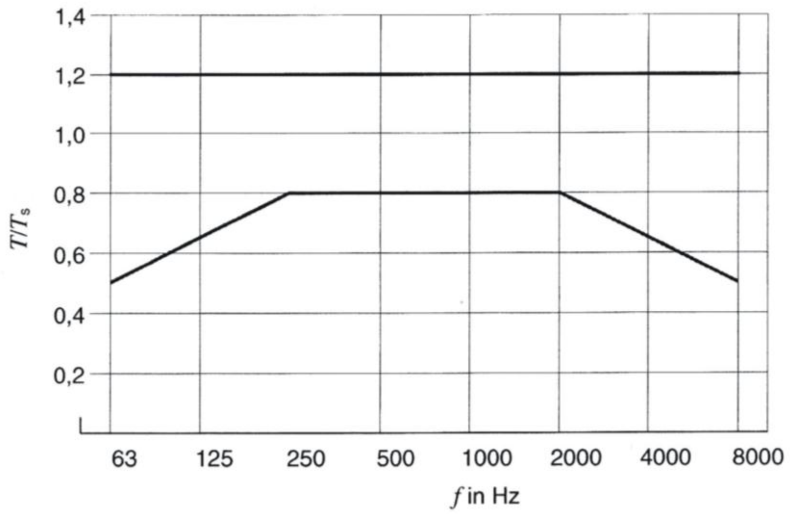


Figure B- 5 Reverberation tolerance range for optimal reverberation for speech, communication and music rehearsal
(ÖNORM; Government Document;*ÖNORM B 8115-1,2,3,4,5*; 2003-09-01)

When the concept of the mid-frequency is introduced, it should be clarified that it is in fact the pitch of the sound as we hear it: 500 Hz is high c in a man’s tenor and 1000 Hz is high c in woman’s soprano voice. This is the difference of 7 tones and so the middle frequencies are in fact the high tones of a woman’s soprano. Reverberation depends on reflection and the frequency of the sound. Reverberation is measured in different frequency segments: octave bands, thirds or very often 6 octave segments. 125-250-500-1000-2000-4000 are mostly used octave bands.

As a final result the line of reverberation is presented; it will differ depending on the fullness or emptiness of the hall. Reverberation and frequency height are related by the principle that in deeper frequencies longer reverberations should be used, and in higher frequencies shorter reverberation time should be used than that measured in the middle frequency of 500 Hz. Others not on the graph above T opt can be gained mathematically to obtain best room acoustics.

For spaces with speech function the optimum reverberation time is calculated with Knudson s formula: T_{opt}=0,32+0,17lg x V (s),

and for concert halls less than 1000m3: T_{opt}= 0,75 + 0,057 3 $\sqrt{V}$ (Watson’s formula)

and for volumes bigger than 1000 m3 T_{opt}=0,9+0,37 3 $\sqrt{V}$ (Watson’s formula).

The Sabine formula is used for places that are not too insulated, the inslation grade of the space being not greater than α_{Raum}=0,3, which represents a middle degree of the sound insulation of the space and is used with calculating for example concert halls.

For places with a short reverberation, for instance studios, Eyering’s formula for reverberation is used: T= 0,163 V/-ln(1-$S_{tot)}$ (s)

α_{Raum}= middle sound absorption grade of the space

S_{tot} total area of the space in m2

V volume of the space in m^3

If we consider reverberations at different frequency heights then the rule for speech curve is that the line of obtained T is identical to T opt the whole way, in all frequencies. (Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999)

On the other hand, the music curve for obtained T should rise by up to 50 % at low frequencies, and these frequencies are less than 250 Hz.

Figure B- 6 Reverberation should be greater in lower frequencies to obtain high quality sound shows that the reverberation in lower frequencies is about 1.5 times greater than in mid frequencies.

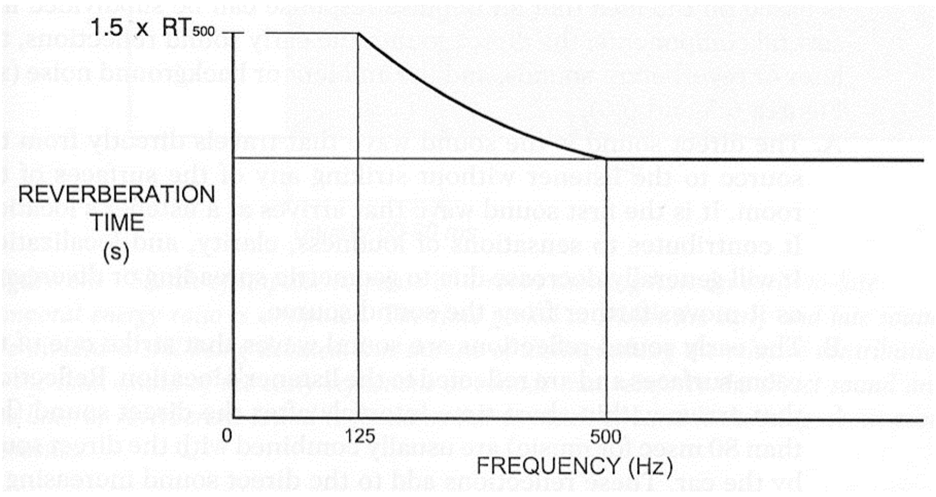


Figure B- 6 Reverberation should be greater in lower frequencies to obtain high quality sound (Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999)

The frequency height of 250 Hz is the height of beginning tone c in a male voice tenor. Achieving the T opt regarding the volume of the space according to for example DIN18041 in the middle frequency field between 500 to 1000 Hz, the goal of obtaining excellent room acoustic characteristics is still not guaranteed.

Before we go further in researching other room acoustical parameters in the same frequency field, first the concept of deep frequencies should be considered. If desired reverberation time is not gained then it is impossible to repair this later with other room acoustic parameters. Because, if the deep frequencies are not controlled, the reverberation in all other frequencies is incorrect. The aim is, therefore to obtain greater reverberation in lower frequencies so we could get the sense of the warmth of the sound. Using this concept, great acoustics for theatres, speech and music regardless of occupancy degree of the hall, can be obtained. The number of people occupying the space is therefore irrelevant if we use this concept of realizing T_{opt} that is 50 percent higher at low frequencies. This is because reverberation is not dependent on occupancy of room at low frequencies.

Very little influence is exerted on reverberation time by the direction the sound comes from. The influence of the angle of the wave falling on a vertical plane is even smaller, and therefore negligible. A µs is one thousand part of a second so that it is evident that the angle of watching of the listener does not have influence on reverberation time.

The posture of the listener has a greater influence when measured at sound pressure level and it is -3 to -8 dB concerning the deviation to straight position of 45 to 135 degrees in a horizontal plane. This is because the head itself is an obstacle for the farthest ear and so the difference is made between sound pressure level which arrives to the closest and the farthest ear. (Fasold;Book;*Scallschutz und Raumakustik in der Praxis: Planungsbeispiele und konstruktive Lösungen*; 1998.)

If reverberation is too long than is optimal for speech, pronounced syllables are covered with past syllables that are still ongoing.

With music, too long reverberation in general means that the sound in the space is too annoying, especially in deeper frequencies, where it could be characterized as mumbling.

With too short reverberation the space could seem dry, the room does not carry the sound, is not supportive and it does not sound alive.

Figure B- 7 Three types of reverberation: dead space, semi reverberant and live space correlated to reduction of sound pressure level which is shown on the y axis.

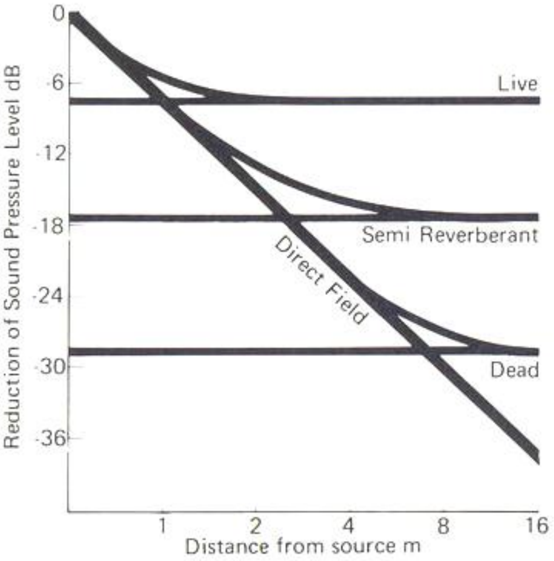


Figure B- 7 Three types of reverberation: dead space, semi reverberant and live space
(Decimin Control Systems P. Ltd. ; Web Page;*Technical information*)

Reverberation does not depend only on the space, but also on the abilities of the speaker or musicians. They can adjust themselves to a space by their interpretation, meaning tempo or the speed of interpretation and with the right dynamics, which is the level of the sound.

Reverberation is measured this way: the sound is measured to decay from -5 to-35 dB below its steady-state value. Then it is multiplied by factor 2 because RT must confirm to the original definition of sound decay from 0 to -60 dB.

If the room contains little absorption it can be rather reverberant. Covering some of the major surfaces with even moderately efficient absorbers will greatly reduce reverberation. Efficiency given with the alpha coefficient is not as important as the total number of absorbing surfaces. Larger areas of less effective materials are just as effective as small quantities of more absorptive materials. Reverberation time is halved with every doubling of absorption. This is shown in a more detailed explanation in the chapter concerning absorption.

The sound of reverberation has no direction, only its loudness and duration can be measured. Reverberance is sound coming and going in all directions at one time. With the reverberation time in a gym the reverberation dies out at the same rate as loudness and lasting, the same number of dB per second, about 12 dB per second and this is then RT of 5 s. Reverberation can be too loud or reverberation can last too long. Adding acoustical material to the hall does change the rate of energy decay in the hall. Reverberation energy is removed by friction between the waves and walls of the hall, not much different than when an ocean wave hits the beach. Reverberation is greater if the volume is greater. Different materials in a hall can contribute to getting the wanted amount of loudness, or time duration of the reverberation. The relation between the loudness and the duration of the reverberation can be altered to get the acoustical characteristics that we want. A good auditorium design will deliver a fairly similar sound pattern to nearly every seat in the house. Voicing the auditorium starts with the sound from loudspeaker. This sound is then amplified with early reflections.

Reverberation: some sound energy is lost with each reflection from a wall and ceiling surface, and even more is lost upon reflection from the audience and seats. Air absorption, which is usually a small additional effect, can become one that is not so small at high frequencies in a very large space. Development of reverberation time initiated architectural acoustics as a science and to this day reverberation remains a fundamental design parameter. In any real indoor space, reverberation time will vary with frequency, sometimes only slightly, but sometimes considerably. When one refers to a single number reverberation time, the reference is usually to the time at 500 or 1000 Hz, or an average of that two.

For many years, achieving the proper reverberation time was considered a prime goal in the design of performing halls along with such important matters as freedom from echo, flutter, focusing effects and unwanted noise. Today, reverberation is considered just one of several important parameters, and some even dispute its importance. In experiments with electronically synthesized sound fields, reverberation time is not judged to be nearly as important as a number of other measures, particularly those dealing with early reflection behaviour, such as the early-to-late ratio and early decay time. In a real space qualities of a hall are interrelated with reverberation time by geometry and it is shown that reverberation time retains considerable significance as an acoustic measure.

B 1.2 Reverberation criteria

See generally (Fuchs;Journal Article;*Planung der Raumakustik Der Nachhall entscheidet*; 2008).

In listening to sound reverberation three important criteria should be considered: the aesthetics in reverberation criterion, the ergonomics in reverberation criterion and the function in reverberation criterion.

The aesthetics in reverberation criterion describes the possibility of a listener to be lifted by the sound, to be fulfilled with the sound and deeply involved in feeling the sound. The aesthetics in reverberation criterion depends on our expectation and comprehension of reverberation in a space. For instance in a Gothic cathedral we expect a long reverberation time and to be totally fulfilled and to be carried on the wings of sound.

The ergonomics in reverberation criterion means that the sound is correctly designed for a specific purpose. Not the same reverberation time should be calculated for a cathedral, an orchestra pit rehearsal room or a conference room, a space for lectures, working bureau or a restaurant.

In addition, here are the examples of reverberation in general dependent on the purpose of the space shown on the Figure B- 8 Reverberation time dependent on purpose in general

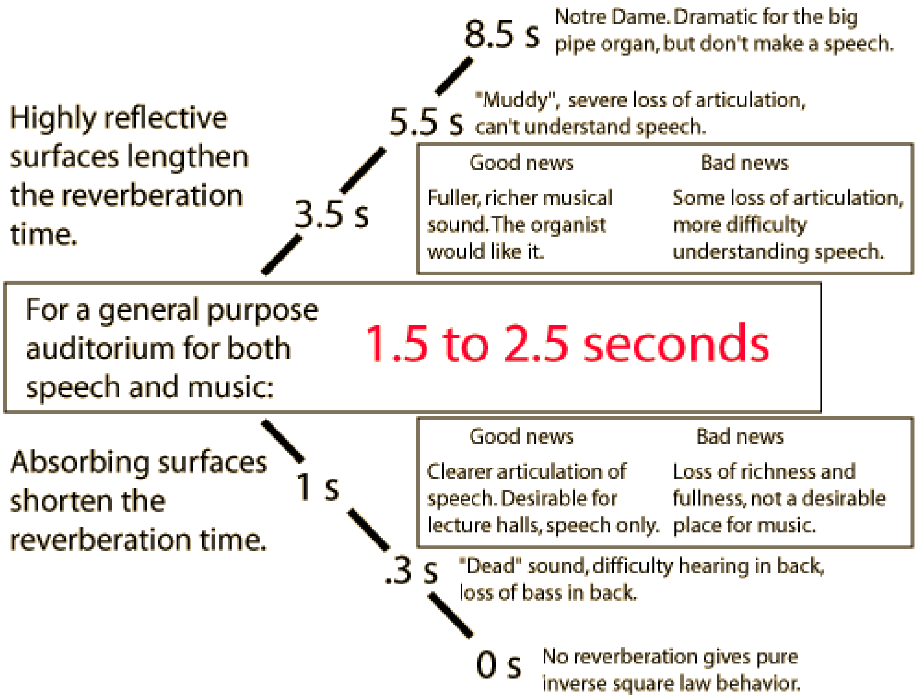


Figure B- 8 Reverberation time dependent on purpose in general

(HyperPhysics by Georgia State University; Web Page; *Sound and Hearing*; 2005.)

The function in reverberation criterion means that no leaking of sound or mis-conduction of the sound is conducted. This is in fact the proper conduction of the sound field over the orchestra towards the auditorium. Means for quality distributions are insulation and absorption of the sound.

B 1.2.1 Occupancy and reverberation

See generally (Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.).

Basic entities of music are the tempo or the speed of the music and dynamics or sound level.

Dynamics does not play a very big role in forming room the acoustics of the space. Tempo has a bigger role. It is proved that on room acoustics the major role has the time when the first reverberation began and that concept is called early reverberation time. That fact contributes to valorising the sitting position in a hall. The greater EDT, the better the place.

In designing the space attention should be drawn to the big influence of occupancy on reverberation time, and that means that one should aim to diminish the difference between reverberation time in a fully occupied space and an empty hall. In an ideal case, the reverberation time should be equal in both cases. At deeper frequencies the difference between a full and an empty auditorium is smaller than at higher frequencies.

Figure B- 9 Relations between EDT in occupied halls versus those in unoccupied halls. Graphs are respectively for low, mid , and high frequencies

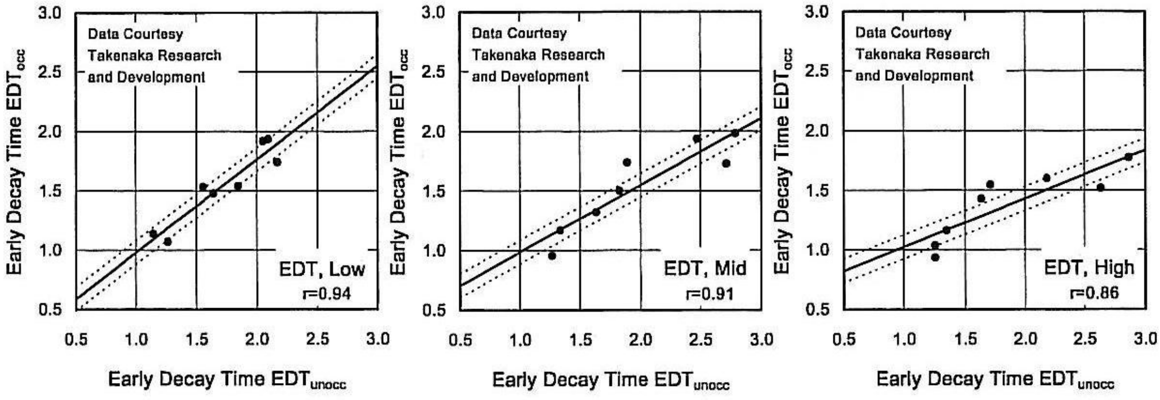


Figure B- 9 Relations between EDT in occupied halls versus those in unoccupied halls. Graphs are respectively for low, mid , and high frequencies (Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

B 1.2.2 Early Decay Time (EDT10), also Early reverberation time

When a musician or ensemble plays rapidly, only the early part of the sound decay process remains audible between successive notes. EDC designates the initial phase of sound decay. In fact EDT is a modified measure of reverberation time. Reverberation time is the time required for a sound to decay 60 db whereas the early decay time is the time the time required for the first 10 dB of decay multiplied by 6 to make a connection to a 60-dB decay. Early decay time was proposed by Jordan: “the later part of reverberation decay ...in speech or music is already masked by subsequent signals once it has dropped by about 10 dB“(Cramer and Muller,1982). A study by Cervone showed a significant relation between EDT and overall acoustic impression rated by listeners at live concert performance (Cervone et al. 1990). It is apparent that EDT indicates acoustical quality better than RT does, because notes played by violinists in symphonic compositions usually follow each other very rapidly. Often the word EDT is replaced by the phrase early lateral reflection because the last better describes what really happened to a sound. So, EDT and early lateral reflection are synonymous. Also, it should be pointed out that in unoccupied halls, the EDT is closely related to the reverberation time RT, for all frequencies. The correlation coefficient r for the six octave bands with center frequencies at 125,250,500, 1000,2000,4000 Hz are respectively, 0.97, 0.98, 0.99,0.98, 0.97 and 0.97.

B 1.3 Reflection

For room acoustics it is very desirable that sound should have obstacles on its way to the listener’s ear because of the phenomenon called sound reflection for in this way the sound is going to be intensified. Whether the sound is amplified electronically or in natural way, the sound level depends on reflection, in other words the number of reflected rays.

Figure B- 10 Reflection in space represents schematic room acoustic movement of the sound impulse

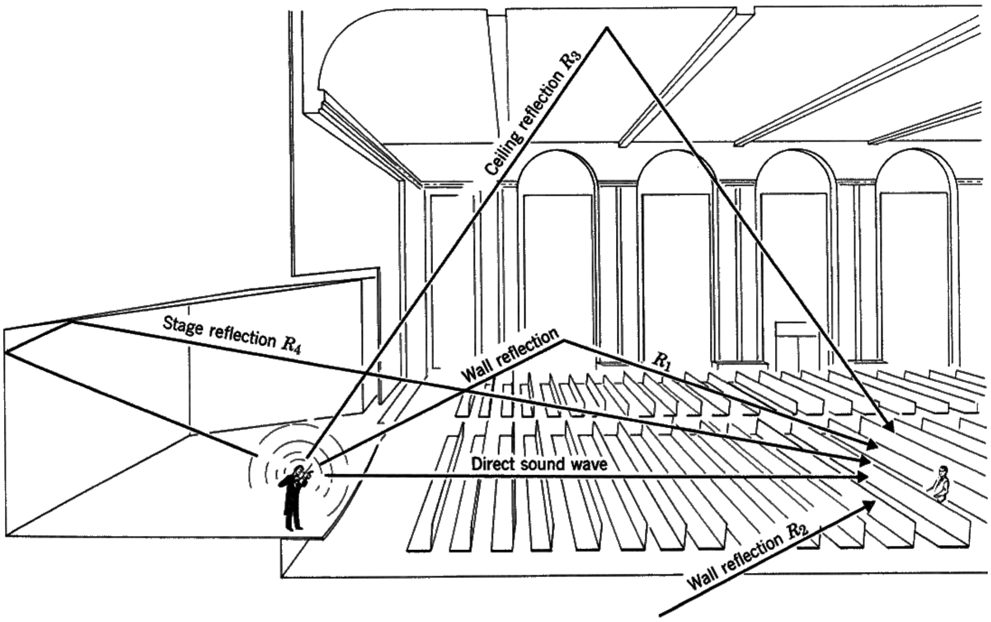


Figure B- 10 Reflection in space

(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

The question is: why reflection contributes to loudness of music, the answer to which lies in the multiplication of sound sources that are all uncorrelated. This means that new sound sources that are every time made with the reflection of a ray are added to direct sound in the calculation of total sound coming to one sitting place. When speaking of reflected sound, we understand that the augmentation of sound is as if coming from this new sound source. Namely, reflection helps the direct sound to add additional dB for every reflected ray is in fact new sound source. So, all these sound sources are added to the sound level of direct sound.

With this knowledge that more reflections mean more sound, we arrive at a revelation of some issues of the thesis about the possibility of defining methodology for superb sound quality.

Namely, when some indefinite variable appears then it means that the formula would have indefinite variable in it. This is not a problem when speaking in mathematically, but in reality and when dealing with concrete procedure, this means that a precise method in fact can never be established because of the indefinite variable that is called reflection.

The sound level of that new reflected sound can be calculated out of the proportion of distance from the direct sound and the distance from that new source minus dissipation loss through the air, which is related to temperature of the air, humidity, and absorption degree of the material. Calculating new sound source power level we should also put into the calculation losses through absorption and dissipation that should be calculated for term δL:

$$Lp=Lw - 20 \log \frac{r}{r_0} - \delta L.$$

r… distance from the sound source

r_0… beginning value of 1 m

δL is calculated out of dissipation through the air and absorption grade of the space.

So, the equation is:

$$Lp=Lw - 20 \log \frac{r}{r_0} -11 \text{ dB} + D$$

The reverberation of some room depends on the reflection grade of the space and its volume. Reverberation is in fact only made out of reflections. The reflection grade of the space is the average sum of reflection grades of walls, ceiling, floor, interior design etc. Reverberation time is also dependent on the largeness of the room. With augmentation of the largeness the dissipation loss through the air grows.

In a closed space the loss of sound power level is smaller than in an open space. This is shown in Figure B- 11 Sound power level in spaces with 3m ceiling or 6 m ceiling height with different absorption grade and in Figure B- 12 Sound power level in a room3 m high correlating to direct sound loss.

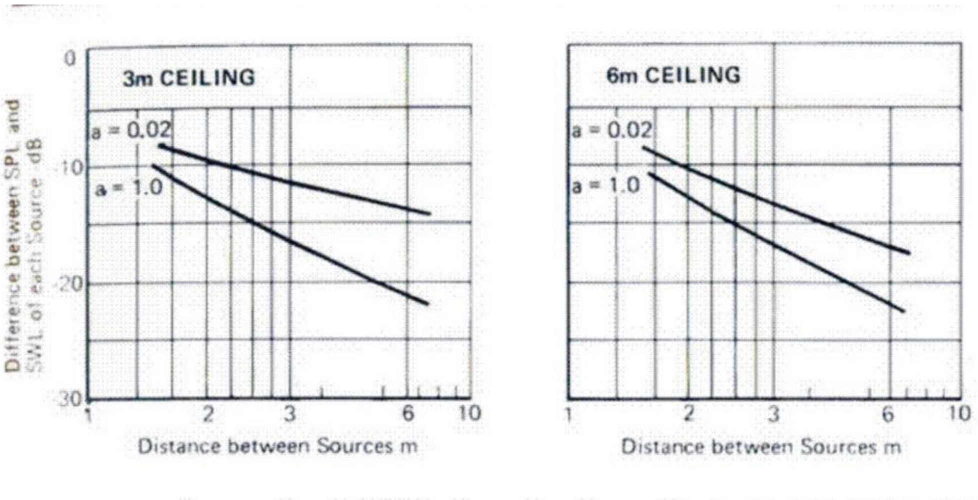


Figure B- 11 Sound power level in spaces with 3m ceiling or 6 m ceiling height with different absorption grade

(Decimin Control Systems P. Ltd. ; Web Page;*Technical information*)

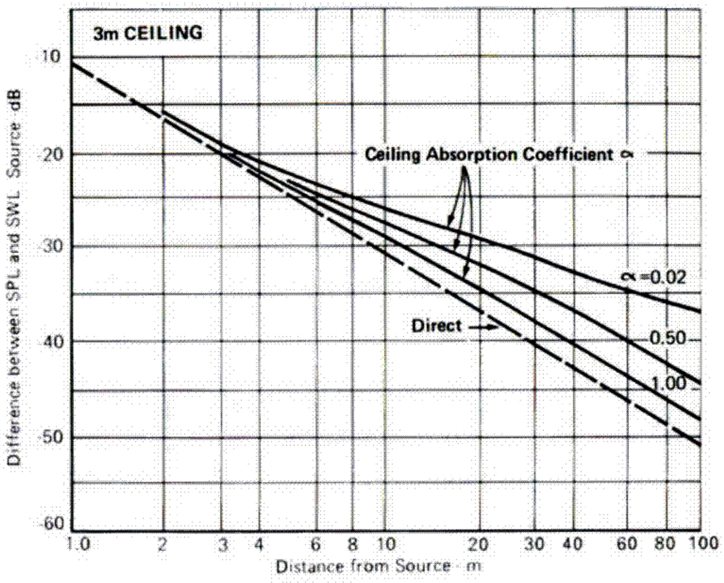


Figure B- 12 Sound power level in a room3 m high correlating to direct sound loss (Decimin Control Systems P. Ltd. ; Web Page;*Technical information*)

See generally (Fuchs;Journal Article;*Planung der Raumakustik Der Nachhall entscheidet*; 2008).

There are three types of reflections that people hear in a hall: early reflections, late reflections and reverberations. Early reflections are good, late reflections are generally bad and reverberation varies between good to bad. The voice of the hall depends on the nature of the sequence of reflections heard by the people in the audience. Outdoors, in the quiet of the desert or after a fresh snowfall it would be necessary to yell to be understood at 7.5 m. This type of acoustic space is one without reflections, anechoic. But, indoors at a distance of 7.5 m the conversation would be clearly heard. The more early reflections there are, the better a person can hear.

There are two ways to make sound louder: With amplifiers, loudspeakers or by adding as many reflections as possible. Adding early reflections raises the apparent loudness of the direct sound in a comfortable, natural way, much more agreeable than with amplifiers. When the object which is a reflection surface is some distance away, the reflected sound will be an echo.

Figure B- 13 Elements of reflection in a concert hall shows what elements the impulse response in a concert hall is made of and the clear relations between reflection, reverberation and echoes are presented. Figure B- 14 Elements of reflection in a cathedral shows the same impulse response in cathedral and in all spaces with great volume.

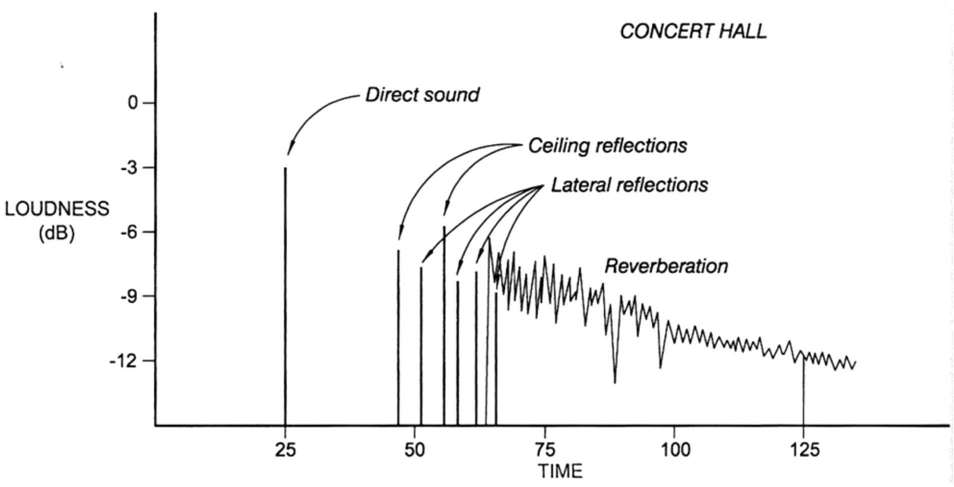


Figure B- 13 Elements of reflection in a concert hall

(Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999)

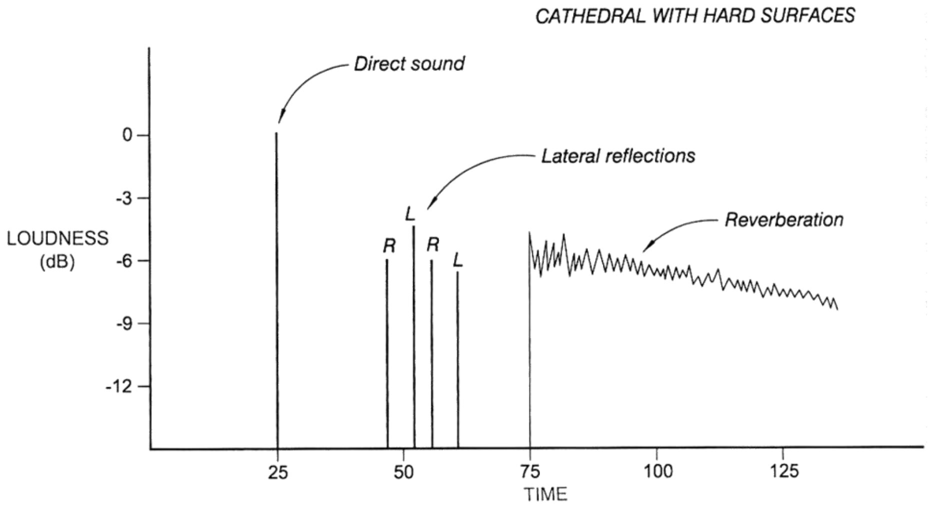


Figure B- 14 Elements of reflection in a cathedral

(Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999)

B 1.3.1 Early reflections

Of all the types of reflections only early reflections actually add to the direct signal to create louder, clearer, intelligible sound. Early reflections have to arrive to the listener within first 60 s, although some scientists say it can be up to 80 ms following the direct sound. The distance from the loudspeaker to the surface providing an early reflection and down to the listener cannot be more than 15 m, better 11.5m further than the direct distance between the loudspeaker and the listener. In this case the early sound is provided and the direct sound is amplified. It is easier to hear an early reflection that is coming from the front, upper or side areas than if the reflection comes from behind due to the position of the ears. Early reflections are the opportunity for the development of a good sound surrounding. These most desirable reflections can be mechanically induced by appropriate positioning and shaping of sound reflecting surfaces. They can also be electronically emulated using a time delayed distributed sound system. Good sounding halls do not misuse their sound systems to create overly loud sounds. They use sound systems to generate a comfortable loudness for the direct sound and then to lead it to the reflector surface that will make the early reflection for a group of listeners. Immediately after early reflection in halls (speech halls) the sound system will ensure an absence of late reflections and finally backfill with a distant sounding reverberation. Early reflections cannot be distinguished from direct sound and that is why they are the only reflections that add to clarity of speech.

All early reflections, those that arrive at the ear within the first 50 ms for speech to 80 ms for music, improve the loudness of the perceived sound. It is desirable and advisable to receive as many as 20 to 40 early reflections. In the best halls the first early reflection comes after 20 ms and it then contributes to the sense of intimacy in the hall. A good, clear and bright sounding hall provides lots of possibilities for many early reflections to reach each seat in the hall.

When speaking about early reflections in the light of the thesis then they confirm the thesis that the method for gaining superb sound can in fact be established. Namely, it is very clear that that early reflections for speech are calculated within the first 50 ms and for music in first 80 ms. The difference between early reflection for speech and for music itself is supportive of the thesis because it shows in which direction the method should be modified for speech and for music.

B 1.3.2 Reflections that contributes to reverberation

See generally (Noxon;Web Page;*Auditorium Acoustics 101,102,103,104*; 2002).

Reverberation is not heard as a distinct set of reflections. Reverberation is a different kind of sound, it seeming to roll. It comes from everywhere at the same time. It is fairly quiet and creates the feeling of largeness, or spaciousness. It is the kind of sound that begins to be felt starting about 250 ms or ¼ second after the direct sound passes by and lasts some 2 seconds. Reverberation is not a series of echoes, the way late reflections are. There is no detectable or measurable direction for sound reverberation. There are no sequences in a sound that we could characterize as a reverberant sound. There are some curious features within a reverberant field. In a large hall composed of distinctly different spaces, each open to another, the reverberation of each separate space can be heard in addition to the reverberation of the main central room. When we are seated under a balcony, reverberation seems to come from the high volume part of the hall out in front. Reverberation is an overflow of chaotic sound stored in a reverberant space. It is not a reflection of a sound wave. Two persons close together are talking in an empty gym and they understand each other but when they are separated by a distance of 9 m they can no longer understand each other. What happens as talkers separate is that the direct sound becomes weaker because of the increased distance until it is finally too weak compared to the reverberant noise level and understanding is lost.

For the thesis proposition it is important to point out that reverberation has been in the historical sense the first criterion for sound quality and that until this day it has stayed the first criterion to be calculated. Not only should reverberation be calculated first, but it is the main criterion from which other, additional criteria should be derived. Reverberation has been studied over the years very thoroughly and reverberation times have been arranged that suit different type of performance, different types of space. There are tables where one just picks the value of the wanted reverberation time and it is then used in further calculation.

B 1.3.3 Late reflections are unwanted

Echo is unwanted segment of reflection.

Echoes are delayed reflections sufficiently loud to annoy the musician or the listeners. Ceiling surfaces that are high enough or that focus sound into one part of the hall may create echoes. Echoes may also result from long, high, curved rear wall whose focal point is near the front of the audience or on the stage. Echoes are more obstructive if a hall has a short reverberation time.

A late reflection that makes reverberations should be relatively quiet, about 15 db below the direct sound. Late reflections, echoes and reverberations obscure understanding of the direct plus early reflections.

This is an example of the late reflection. When the distance between direct sound and a reflection surface is smaller than 11.5 m echoes could not be heard. In fact one will receive early reflection sound that amplifies the direct sound. Generally, people can just begin to detect echoes if they arrive about 60 ms after the direct signal arrives, about 1/16th of a second. With the speed of 330 m/s it is a round trip of 23 m, or a distance of 11.5 m is the distance at which a listener could hear an echo. Late reflections are all those reflections that are distinguishable as separate acoustic event from the direct signal. Echoes are late reflections. Multiple reflections, strings of echoes are also late reflections. Late reflections are those that arrive after about 60 ms following the reception of the direct signal. They can stretch up to around 250 ms that is ¼ of a second or so. Their characteristic is that when one concentrates it is possible to identify where some of them come from. When too many are coming they cannot be separated in terms of direction or timing but are still hearable as being separate from the sound of the direct signal. There are two methods to eliminate late reflection: absorption and diffusion. If late reflections are absorbed, they are removed from the sonic space entirely and the overall loudness of the subsequent reverberation is perceptibly reduced. If late reflections are diffused, scattered about, they are not removed from the sonic space and the reverberation remains loud. Late reflections are generally bad for clarity or intelligibility of the sound. In designing a hall it is important to reduce late reflection and too dense early reflection by adding early reflection surfaces in the surrounding area of the player, or the speaker that should not exceed 11.5 m as defined above, because in this range of distance only the early reflections are made.

We need to accomplish make sure that the potential of reflection is realised at every barrier and this is in general what helps to prevent types of standing waves.

A standing wave is another unwanted phenomenon. It is important to realize that standing waves may form at an almost infinite number of multiples of lowest frequency so there are really only two solutions: avoid a square room or absorb/diffuse sound on the back wall.

Segments of reflections that we do not want to occur: whitened scene, echoes, noise, tonal distortion, and non-uniformity of hearing conditions.

The space also should not be too absorbent.

Longer (bass) waves contain more energy, so they are harder to absorb evenly. This is because these low frequencies are in general not absorbed and there are a much greater number of these waves around us, so the final effect is that bass is louder. Bass waves bounce from boundary to boundary, seeking the path of least resistance, a full cycle or half cycle. Consequently, the length of travel determines the frequency. Waves travelling in one direction interact with those travelling in the opposite direction. This phenomenon is referred to as a standing wave. A standing wave is in fact producing of spots in a space of no sound at all because of the superposition of sound waves resulting in 0 dB.

When mid-range frequencies interact with those travelling in the opposite direction, the effect is known as flutter.

As with early reflections from all said above we see that there is a time limit determined where late reflection begins. Late reflections should be diminished as much as possible. This fact also contributes in finding the right method for obtaining quality sound.

B 1.3.4 Reflection grade and reflection inclination

On the Figure B- 15 Reflection, absorption and transmission at a barrier we can see basic concept of sound absorption and sound transition:

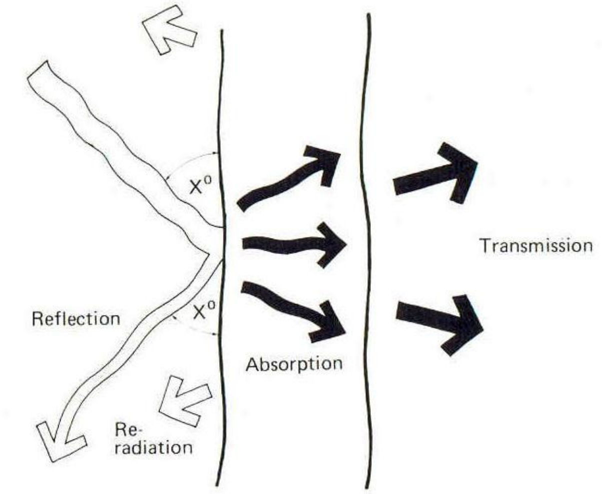


Figure B- 15 Reflection, absorption and transmission at a barrier
(Decimin Control Systems P. Ltd. ; Web Page;*Technical information*)

The part of the sound shown through sound power W is reflected.

Sound absorption grade:α= $\frac{W_{abs}}{W_1}$

W1 is total sound power that hits the obstacle and is reflected.

Reflection grade and absorption grade are related as follows: ρ+α = 1. α values are from 0 to 1. For reflection the same rule is valid.

Here it should be pointed out that $\rho+\alpha = 1$ is just a simplification of relations between these coefficients. In fact α is derived through W that stands for energy and ρ is derived from p pressure and we know that pressures are always calculated with p^2 so the relation is in fact $\rho^2+\alpha = 1$

Reflection is the opposition of absorption and their sum of absolute values for the same material in the same condition is always 1. If the grade of absorption is 1 then it means that the material is totally absorptive; this is only in some ideal case or imaginary case and is used only theoretically. Equivalent sound absorption area A equals: $A=\alpha xS$ (m2). The total sound absorption area is the sum of all equivalent sound absorption area: $A= \alpha_1 xS_1 + \alpha_2 xS_2......=\sum \alpha_n xS_n$ (m2)

Reflection of the sound can be presented in the same way as a light ray, because light is also of the wave nature in optics. (Meyer;Book;*Kirchenakustik*; 2003)Therefore, the angle of incidence

is the same as the angle of reflection of the same ray.

Figure B- 16 Acoustic screening and Figure B- 17 Reflection on different surfaces show general rules for reflection inclination

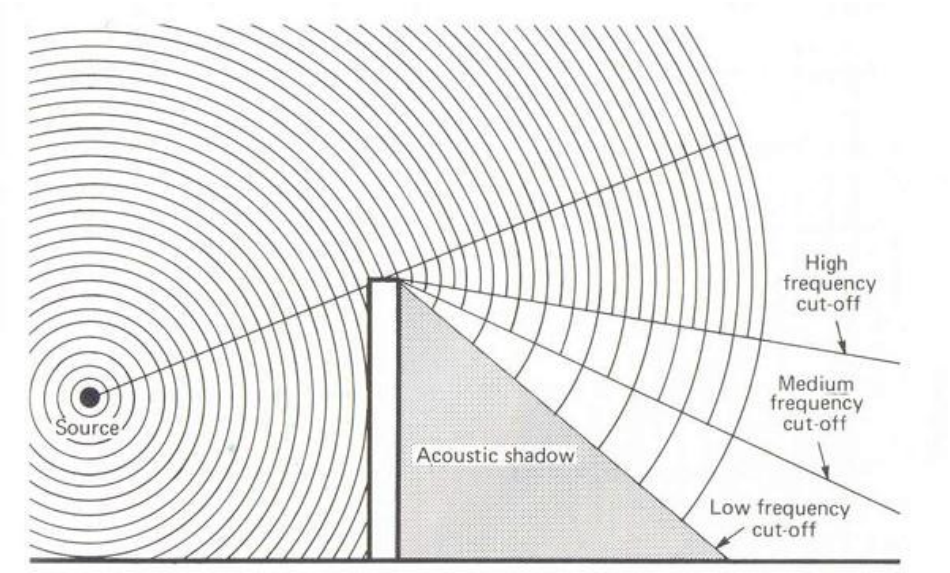


Figure B- 16 Acoustic screening

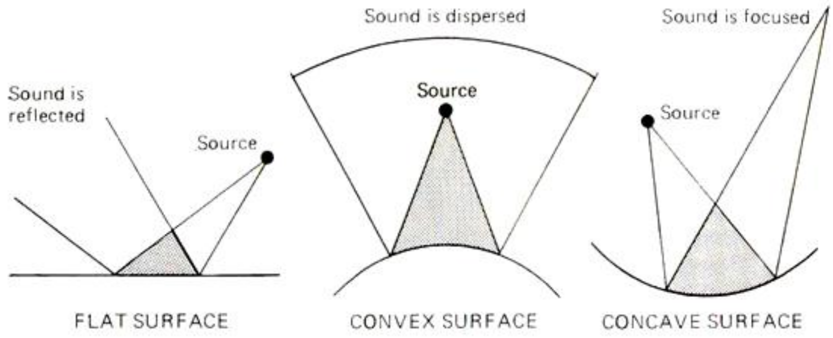


Figure B- 17 Reflection on different surfaces

(Decimin Control Systems P. Ltd. ; Web Page;*Technical information*)

Figure B- 18 Reflection of sound on round surfaces. Pictures are respectively from left to right cases: a, b, c, d

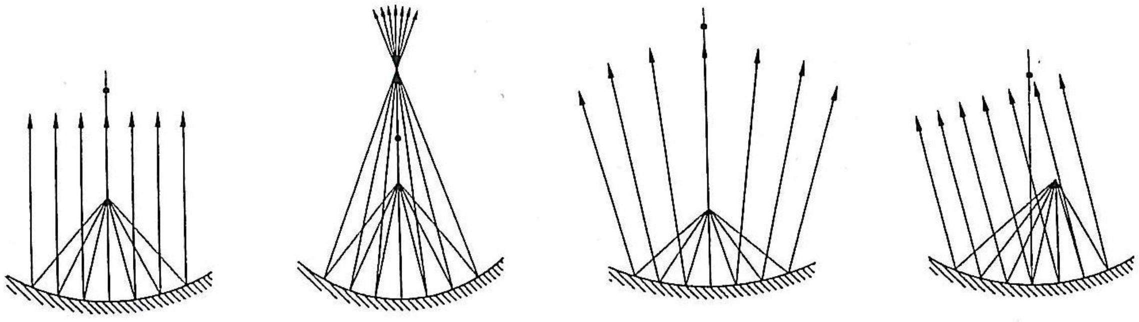


Figure B- 18 Reflection of sound on round surfaces. Pictures are respectively from left to right cases: a, b, c, d
(Meyer;Book;*Kirchenakustik*; 2003)

.r... the center of roundness, s...the distance between sound source and reflection area, e...the distance between focal point and reflection surface. The relation between these conditions is:

$$\frac{1}{s}+\frac{1}{e}=\frac{2}{r}$$

Explanation for picture a: s= $\frac{r}{2}$ rays are going to be reflected in parallel. In the b picture s is greater than $\frac{r}{2}$ so a focal point is going to be created. If a sound source is situated in the same spot as the radius of roundness=r then the focal point will also be at the same spot, which means that the sound is coming back to the source. Picture c s is shorter than $\frac{r}{2}$ and the reflection is acting as if reflected from behind rounded wall. In the same way reflection from a convex wall is formed. This information about enlargement of the sound level at one point, that is, the focal point, could be used in way of collecting the sound in this spot with microphones and then spreading it with loudspeakers. Equipment that worked on this principle was used for instance in a church in Hannover, the Marktkirche long before microphones were invented.

B 1.4 Absorption

See generally (Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999).

Softer surfaces such as a carpeted floor absorb the treble, higher range of frequencies and reflect the bass range. Other surfaces work nearly in an opposite manner. A glass window will reflect the treble range sound and let the bass leak right out of the hall, in other words to be diminished. Hard surfaces such as a concrete floor reflect all the sound.

No material is perfectly reflective or perfectly absorptive. In general, materials with coefficients below 0.2 are rather reflective, and those with coefficient of 0.80 are very absorptive.

Acoustical sound absorbing materials should only be used when necessary to eliminate echoes or acoustical glare and then in areas as small as possible

Absorption depends on frequency. Therefore, in tables the absorption degree is represented in relation to frequency height.

In Figure B- 19 Reduction of reverberation in correlation to absorption before and after we can trace how reverberation is related to absorption. In the figure we can see the relation between absorption A1 which is a smaller absorption grade and A2 which is a bigger absorption grade. If we insert real numbers in the formula NR=10 log $\frac{A_2}{A_1}$ we get A_1=100 m2; A_2= 100+800=900 m2; NR= 10log $\frac{900}{100}$ = 10 log 9= 9.5 dB

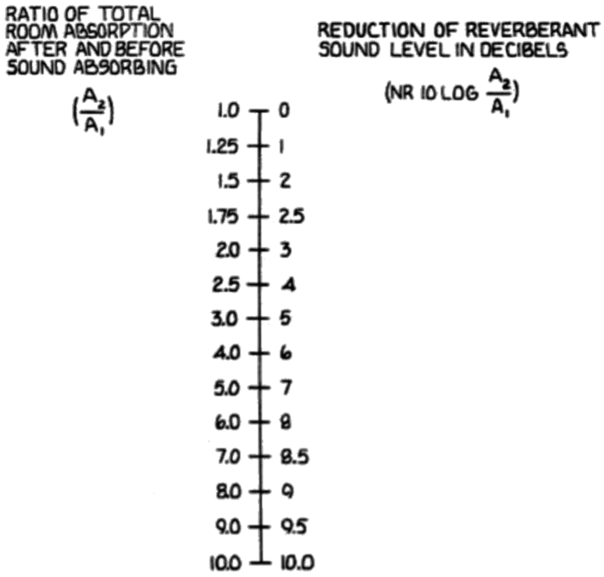


Figure B- 19 Reduction of reverberation in correlation to absorption before and after (Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999)

B 1.4.1 Absorption versus insulation

There is often a confusion between sound insulation and sound absorption. Absorption is connected to sound effects in one room and term insulation is used when transmitting sound from one room to another. Insulation means: in this case the prevention of the transmission of sound from one room to another. Sometimes one can find that the word insulation is replaced with the word isolation, but this is in fact a change of a linguistic nature and the correct usage is the word insulation.

Materials in two segments contribute to sound diminishing. The first segment is the sound absorption and the second segment is sound transmission loss or insulation or insulation. Absorption means that the sound energy is diminished in material itself and less of the sound is reflected. Transmission loss is a term in acoustics is used when we want to describe how much of sound is stopped through the material into and will not be transmitted into next room and is measured in for example 40 dB.

A sound striking the boundary of the room is partially reflected, partially absorbed, and partially transmitted to the next room. The first two processes are mutually exclusive and they both fall in the field of architectural acoustics. When talking about the material absorption potential, we in fact talk about acoustical insulation.

The third process, transmission, falls into the field of sound insulation.. The issue is not how much of the sound is reflected or absorbed, but how much of it is allowed to pass through the boundaries. The percentage of energy transmitted tends to be very small; the transmission loss would be about 20 dB.

In context of the term transmission loss the term attenuation is often used.

Figure B- 20 Absorption versus insulation shows the sound insulation in dB in relation of energy transpassed. Transpassed energy is dependent upon absorption of material.

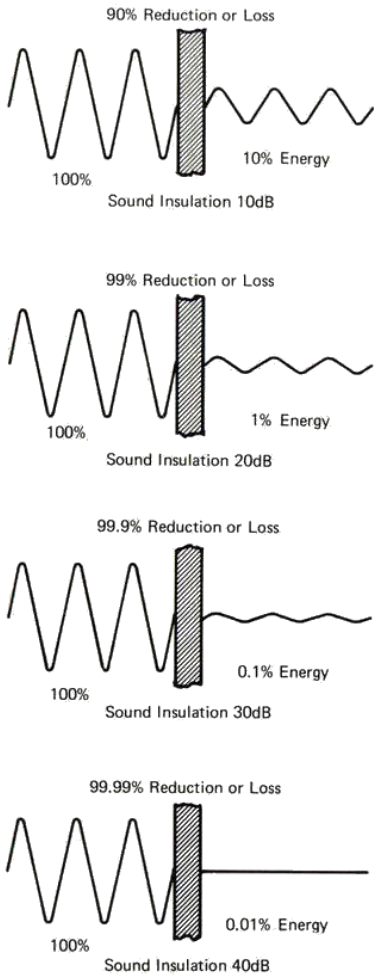


Figure B- 20 Absorption versus insulation
(Decimin Control Systems P. Ltd. ; Web Page;*Technical information*)

The average sound transmission loss, average from 125 to 4000 Hz, increases with increasing weight. For instance a plaster wall of 5 cm would have an average sound transmission loss of about 35 dB. Doubling the thickness of the plaster to 10 cm would increase sound transmission loss to 40 dB. A plaster wall 15 cm thick would have TL of 45 dB.

Sound insulation is required in order to eliminate the sound path from a source to a receiver such as between apartments in a building, or to reduce unwanted external noise inside a concert hall. Heavy materials like concrete tend to be the best materials for sound insulation -doubling the mass per unit area of a wall will improve its insulation by about 6dB. It is possible to achieve good insulation with much smaller mass by instead using a double leaf partition (two separated independent walls).

Figure B- 21 Mass low curve illustrated or how absorption is correlated to greater mass of materials

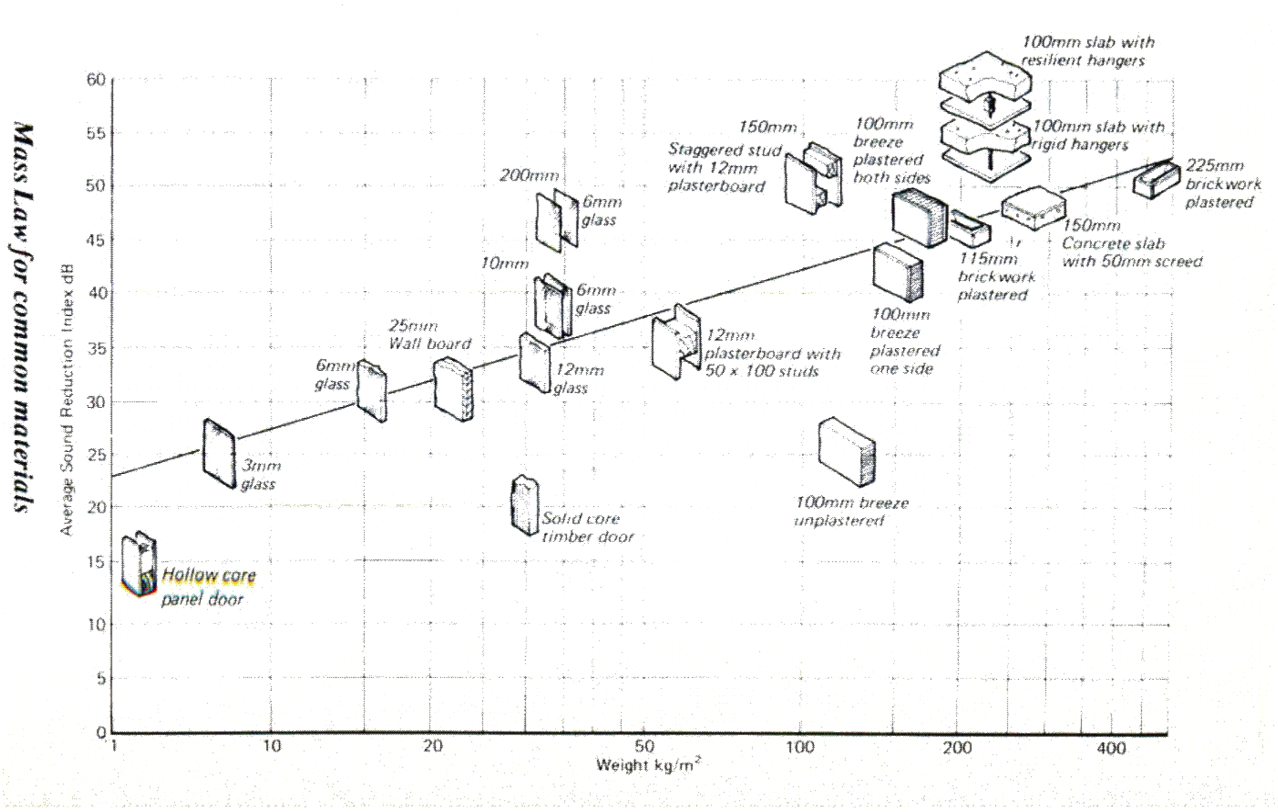


Figure B- 21 Mass low curve illustrated or how absorption is correlated to greater mass of materials (Decimin Control Systems P. Ltd. ; Web Page;*Technical information*)

If 5 cm plaster were split into two independent 2.5 cm leaves and separated by 7. 5 cm of airspace, an average increase of about 8 dB would be the result. From the figure the increase would be 2 dB at 125 HZ and 12 dB at 4000 Hz.

Double –layer construction is the way to overpass great mass gain limits of single, homogeneous partition materials. In addition to optimizing the sound insulation performance of various building elements, consideration is also given to improved methods of connecting and sealing of the elements so that the maximum sound transmission loss could be realized. Degradation in performance by some 23 dB from a partition element potential performance of more than 50 dB is gained in a typical field situation. With lightweight operable or demountable partition systems that are made of numerous panels the problem of sound leaking is even more significant. Airspace of less than 4 cm does not really much improve the sound transmission loss. This is why some windows do not have an excellent sound TL characteristics even though adequate thermal insulation may be achieved. Further improvement of double construction is adding cavity absorption in double construction. Fibrous, glass or mineral wool type insulation materials within the air cavity can reduce the sound transmission further and thus reduce the overall sound energy loss through the construction. If the construction is such that the two sides are extensively coupled together by an internal support system, the cavity absorption will scientifically less effective than if two sides are well insulated from one another. Cavities of double construction provide muffler like effect of reduced sound and also are adequate for electrical conduction. The sound insulation via the ceiling path or via air conditioning system must be at least equivalent to that via the common partition between the adjacent rooms. That is obtained by putting vertical elements in the path of the sound or by putting horizontal elements on the back side of the ceiling. When sound insulation between rooms should be greater than about 50 dB extraordinary care in designing and putting in place of all possible flanking path is necessary. The control of all undesired sound, from exterior spaces, adjacent spaces, can mask significant parts of the desired sound. Small conference or classrooms, where speaker-to-listener distances are small, are less demanding then larger performance auditoria.

The weak point for sound transmission to and from a building is most often via the windows. Double glazing will usually afford noticeably better protection then single glazing, but in areas of high external noise it might be preferable to have double windows with a large air gap and acoustic absorbent material in the reveals. A drawback of improving external insulation is that, for some people, the resultant lower background level can itself be disturbing; it can also make noise transmission through party walls more apparent.

Sound absorption occurs when some or all of the incident sound energy is either converted into heat or passes through the absorber. For this reason good sound absorbers do not of themselves make good sound insulators. Although insulation and absorption are different concepts, there are many instances where the use of sound absorbers will improve insulation. However absorption should not be the primary means of achieving good sound insulation.

B 1.4.2 Absorption by friction versus absorption by resonance

All remaining energy is partly reflected and partly absorbed. Contrary to popular belief, a broken up surface does not absorb sound though it may diffuse or scatter it in many directions.

The processes that result in acoustical absorption are friction and resonance. Therefore we distinguish two types of material: porous absorbers and resonant absorbers. Totally simplified for easier memorization: absorbers and resonators.

Absorption through friction occurs when sound has access to the fine pores that one finds in porous and fibrous materials. The energy thus lost is converted into heat. Most of the materials whose purpose is to absorb sound are based on this principle. These materials are just absorbers.

Absorption through resonance occurs when for example a Helmholtz resonator is set in motion by sound. The system will absorb and dissipate the energy if its natural frequency corresponds to that of the incoming sound. Few products use this principle by design but many building materials will if not restrained resonate and thus absorb sound. Absorption is frequency-dependent.

Porous-fibrous absorbers are most efficient in the higher frequencies but also perform well in the middle and low frequencies if sufficiently thick or if backed by airspace.

Resonant absorbers work best in the low frequencies and are quite reflective in other frequencies. Resonators are membrane materials like for instance plate oscillators, perforated plate oscillators or Helmholzrezonator.

For needs of absorption in spaces two types of absorber are used: porous absorbers and resonators. The main difference between these two types of absorbers, porous absorbers and resonators, is as shown in the picture, for porous absorbers are used in middle frequencies, and resonators for field of resonance, it is to say at deep frequencies.

Figure B- 22 Absorption of porous Absorbers and resonators

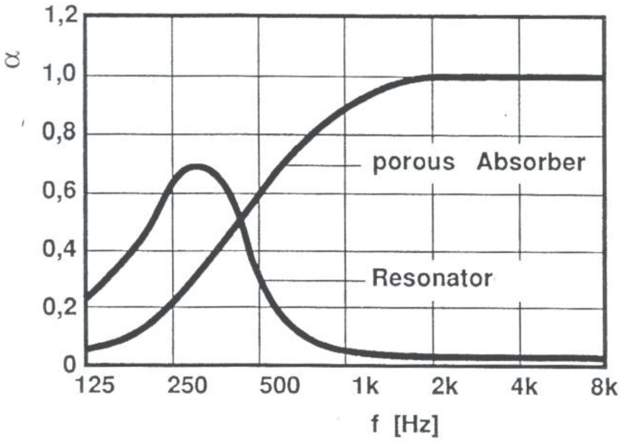


Figure B- 22 Absorption of porous Absorbers and resonators

Figure was translated from the author of the dissertation (Fasold;Book;*Scallschutz und Raumakustik in der Praxis: Planungsbeispiele und konstruktive Lösungen*; 1998.)

Dissipative absorbers are in fact porous materials in the group of absorbers by friction. Porous absorbers are carpets, fibreglass/mineral wool, drapes, and cavity absorbers are type of resonance absorbers.

Membrane absorbers are in the resonance absorbers group of materials. Membrane absorbers are thin types of different board materials.

Figure B- 23 Absorption for different types of absorption shows the major frequency regions that are absorbed by three type of material: cavity absorber, membrane absorber and dissipative absorber.

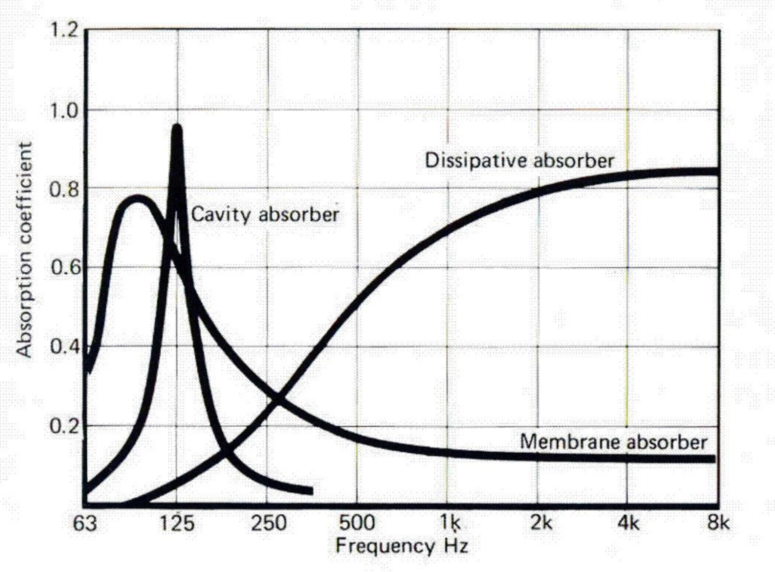


Figure B- 23 Absorption for different types of absorption

(Decimin Control Systems P. Ltd. ; Web Page;*Technical information*)

B 1.5 Absorption of materials

Generally speaking, the amount varies between almost no absorption in concrete and mortar, and almost total absorption of an auditorium which is fully occupied. The sound absorbing efficiency of material is given by its sound absorption coefficient alpha α. The sound absorption coefficient is a ratio of the incident sound to the reflected sound and may vary from 0, which means no absorption, or perfect reflection to 1, which means complete absorption, or no reflection. Sound absorption coefficients are determined from laboratory measurements.

For reducing echoes the efficiency of the material of for instance the rear wall is of the essence. BRICK owing to its considerable mass of about 2100 kg/m3, brick attenuates airborne sound very well. Exceptionally high orders of attenuation can be achieved with two side-by-side but unconnected brick walls. Joints must be fully mortared or otherwise sealed.

Absorption is negligible since there is little or no porosity and the material is rigid.

1) CONCRETE of normal weight is 2300 kg/m3 is among the best attenuators of airborne sound. Lightweight concrete is less effective. Concrete provides virtually no absorption. Aerated concerts can be fairly absorptive.

2) CONCRETE MASONRY UNITS are modular building blocks made of concrete usually fabricated with a hollow core. Because of its weight it provides good attenuation. Two unconnected concrete masonry walls like those of brick can provide exceptionally high orders of attenuation. Since its surface is somewhat porous concrete masonry is slightly absorptive unless painted or otherwise sealed. If well sealed it becomes a good all-frequencies reflector.

3) GLASS despite its mass of 2500 kg/m3 it is marginal sound attenuator because it is thin. Superior performances are provided by double glass and laminated glass. Glass is totally reflective in the higher frequencies and because of the fact that glass resonates it can absorb appreciable amount of low frequencies.

4) GYPSUM BOARD is fire resistant material although not very heavy 800 kg/m3 it can provide a fair amount of attenuation because it is used with multiple layers of gypsum with resilent partition and absorptive material in air cavity space. Gypsum, unless attached directly without airspace to solid surface, resonates and thus absorbs low frequency sound. At higher frequencies it is highly reflective.

5) PLASTER skins applied to studs or joints attenuate the sound like gypsum boards. Plaster provides very little absorption in the low frequencies, if suspended or furred out from a solid surface. Acoustical plaster was originally intended to create jointless surfaces that absorb sound, which ordinary plaster does not. It is not a reliable absorber because it depends on correct mix and application method.

6) PLYWOOD is a laminate of several layers of wood veneer mass is 600 kg/m3 and is not a good attenuator. Thin plywood is low frequency absorber. In high frequencies it is quite reflective.

7) RESILIENT TILE is one of a family of floor tiles that especially if foamed back provide some attenuation of high frequency. They are reflective as concrete or other hard floor finishes.

8) STEEL is not used for attenuation because its weight in reinforced concrete is negligible. Steel is highly reflective unless free to vibrate and then tends to absorb low frequencies by resonance.

9) STONE with its weight it is a good attenuator, but if used as a paving it has no impact on insulation. Marble is among the acoustically most reflective materials, but there are stones that are porous and are not that reflective.

10) WOOD owing to its low weight it is of middle attenuation. Wood decks are generally reflective, but unsealed cracks between the boards contribute to fair amount of absorption. Wood panelling absorbs low frequencies sound by resonance and may lead to serious bass absence unless it is thick and restrained to the wall without airspaces.

11) ACOUSTICAL MATERIALS. ACOUSTICAL DECK is made of structural material backed with absorptive material. It absorbs sound from about 0,5 to 0,9. If exposed it can greatly reduce noise and reverberation in spaces such as gyms, factories.

12) CARPET is the only flooring material that absorbs sound in range from 0,2 to 0,5 dependent on thickness and it absorbs mainly high frequencies. Carpet also attenuates impact sounds because it prevents hard contact with the floor. If sufficiently thick, it can be extremely effective. However, on wood floors, it will not eliminate low frequency thuds.

13) FIBER Cellulose and mineral fibre make the basis of wood wool, acoustical tiles, fibrous sprays and these all materials are designed to absorb sound.

14) CURTAINS absorb the sound if they are reasonably heavy 500 kg/m3 and if they are dense. Fabrics attached directly to hard surface do not absorb sound. However if stretched over fibreglass and dense they are excellent absorber.

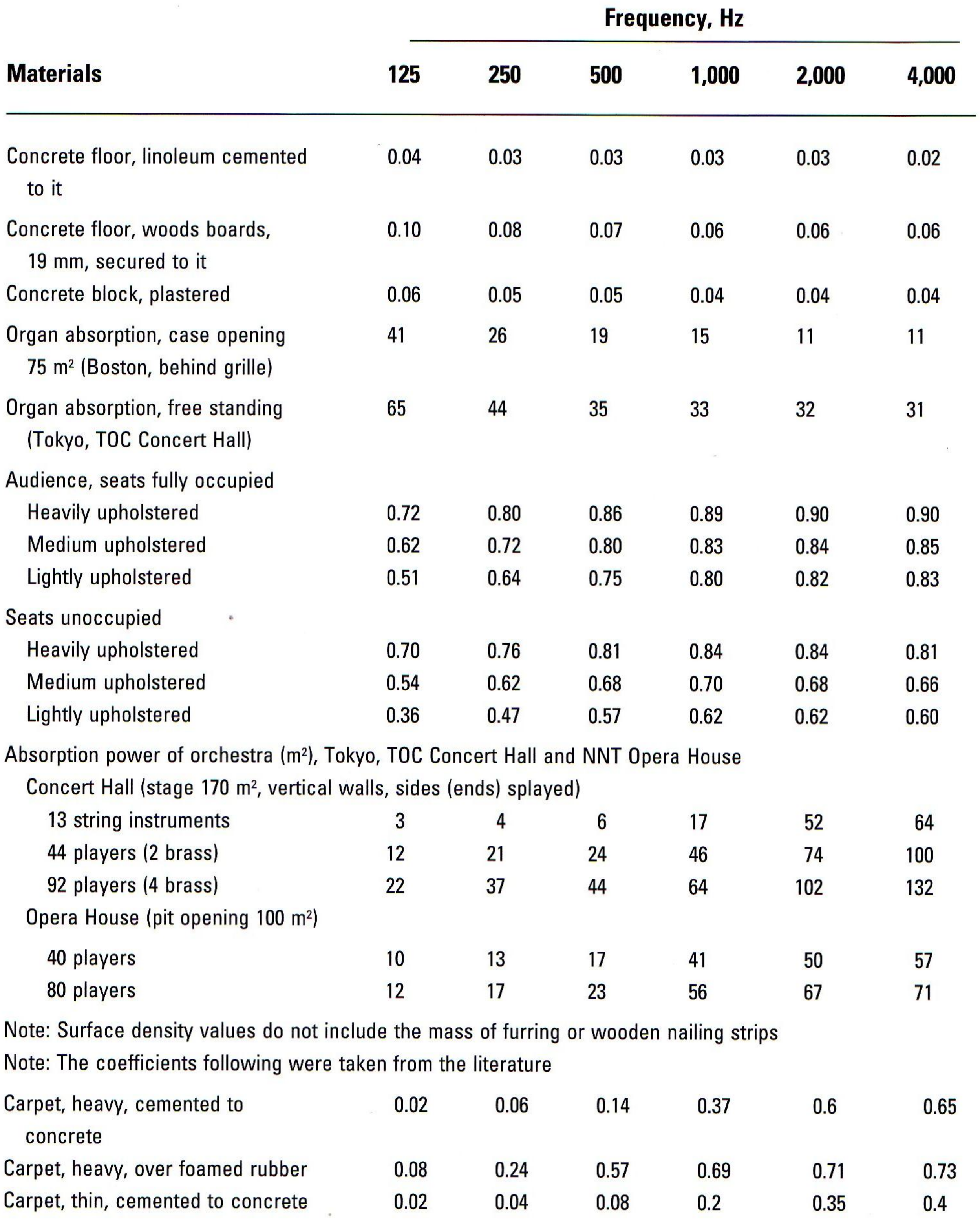
15) FIBERGLASS is available in the form of blankets, boards and spray and is an excellent absorber.

16) SEALANTS are used to seal joints and cracks in many construction types. They are used to make other materials effective in their attenuation and have to be properly applied.

17) SLATES AND GRILLS if widely spaced have a role to protect the fibreglass behind them but if they are of increased size and the space between them is reduced then they are primarily reflectors.

Figure B- 24 List of materials and their absorption values shows absorption grade in usual octave band frequencies

	Frequency, Hz						
Materials	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**	**Mass, kg/m^2**
Gypsum, 2 layers, fiberglass reinforced, 25 mm w/lighting and ventilation	0.15	0.12	0.10	0.08	0.07	0.06	40
Note: Gypsum, plaster board, not reinforced, mass per m^2 equals [thickness in mm] × 1.0 kg/m^2, approximately							
Wood, ceiling, 2 layers, 28 mm w/lighting and ventilation	0.18	0.14	0.10	0.08	0.07	0.06	17
Wood, sidewalls, 1 layer, 20 mm w/doors and lighting	0.25	0.18	0.11	0.08	0.07	0.06	12
Wood, sidewalls, 1 layer, 12 mm w/doors and lighting	0.28	0.22	0.19	0.13	0.08	0.06	6.2
Wood, audience floor, 2 layers, 33 mm on sleepers over concrete	0.09	0.06	0.05	0.05	0.05	0.04	N/A
Wood, stage floor, 2 layers, 27 mm over airspace	0.10	0.07	0.06	0.06	0.06	0.06	17
Wood, 19 mm, over 25 mm compressed fiberglass, screwed to 150 mm concrete block w/doors and lighting	0.20	0.15	0.08	0.05	0.05	0.05	N/A
Plaster, ceiling, 60 mm w/lighting and ventilation	0.10	0.08	0.05	0.04	0.03	0.02	60
Plaster, ceiling, 30 mm w/lighting and ventilation	0.14	0.12	0.08	0.06	0.06	0.04	30
Plastic, fiberglass reinforced phenolic foam, filled with aluminum hydroxide, faced with very thin layer plywood, 8 mm (Tokyo, Hamarikyu-Asahi Concert Hall)	0.25	0.23	0.16	0.12	0.11	0.10	4



	Frequency, Hz					
Materials	**125**	**250**	**500**	**1,000**	**2,000**	**4,000**
Concrete floor, linoleum cemented to it	0.04	0.03	0.03	0.03	0.03	0.02
Concrete floor, woods boards, 19 mm, secured to it	0.10	0.08	0.07	0.06	0.06	0.06
Concrete block, plastered	0.06	0.05	0.05	0.04	0.04	0.04
Organ absorption, case opening 75 m² (Boston, behind grille)	41	26	19	15	11	11
Organ absorption, free standing (Tokyo, TOC Concert Hall)	65	44	35	33	32	31
Audience, seats fully occupied						
Heavily upholstered	0.72	0.80	0.86	0.89	0.90	0.90
Medium upholstered	0.62	0.72	0.80	0.83	0.84	0.85
Lightly upholstered	0.51	0.64	0.75	0.80	0.82	0.83
Seats unoccupied						
Heavily upholstered	0.70	0.76	0.81	0.84	0.84	0.81
Medium upholstered	0.54	0.62	0.68	0.70	0.68	0.66
Lightly upholstered	0.36	0.47	0.57	0.62	0.62	0.60
Absorption power of orchestra (m²), Tokyo, TOC Concert Hall and NNT Opera House						
Concert Hall (stage 170 m², vertical walls, sides (ends) splayed)						
13 string instruments	3	4	6	17	52	64
44 players (2 brass)	12	21	24	46	74	100
92 players (4 brass)	22	37	44	64	102	132
Opera House (pit opening 100 m²)						
40 players	10	13	17	41	50	57
80 players	12	17	23	56	67	71
Note: Surface density values do not include the mass of furring or wooden nailing strips						
Note: The coefficients following were taken from the literature						
Carpet, heavy, cemented to concrete	0.02	0.06	0.14	0.37	0.6	0.65
Carpet, heavy, over foamed rubber	0.08	0.24	0.57	0.69	0.71	0.73
Carpet, thin, cemented to concrete	0.02	0.04	0.08	0.2	0.35	0.4

Figure B- 24 List of materials and their absorption values

(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

B 1.5.1 Special materials and special conditions for placing absorbent materials in the space

Special materials in this chapter are: reflectors, resonators, diffusors. Some special conditions that are subject of this chapter are: reflector distance from the wall, painting reflectors, holes in reflectors, contribution to absorption of air spacing in placing materials.

Porous materials are most of the prefabricated factory –finished products available. The overall thickness including any spacing of the material from a backup surface influences the absorption in the low frequency range. The thicker the porous material and the deeper the air space behind the absorbing layer, the higher the low frequency absorption coefficient will be. The surface facing applied to or on the porous material because of architectural finish reasons like durability, light reflectance, appearance influences high frequency by decreasing the coefficient in higher ranges. Sound reflection from the solid areas between openings, perforations, or fissures of a surface facing material tends to reduce absorption coefficient at higher frequencies.

Reflectivity of one plate (resonator) depends on the border of frequency coincidence, then on dimensions of the plate and how much can it swing. The bigger the plate is, the smaller the reflectivity is. Distances between plates and the ability to swing improve their reflectivity. The minimum distance between plates should be 0.5 m.

In the world of materials we know types of specially designed elements that are called reflectors that have alpha rather low, about 0.2 or so, resonators are materials that absorb sound by process of resonation, diffusors are elements that scatter sound to avoid unwanted echoes in the sound field.

Figure B- 25 Schematic presentation of diffusion shows diffusors on the ceiling Figure B- 26 shows the diagram, real presentation of that special element and its dimensions.

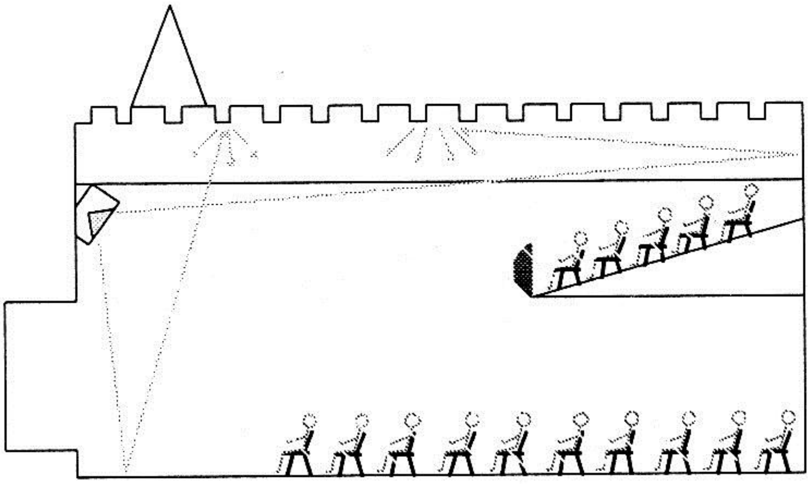


Figure B- 25 Schematic presentation of diffusion
(Noxon;Web Page;*Auditorium Acoustics 101,102,103,104*; 2002)

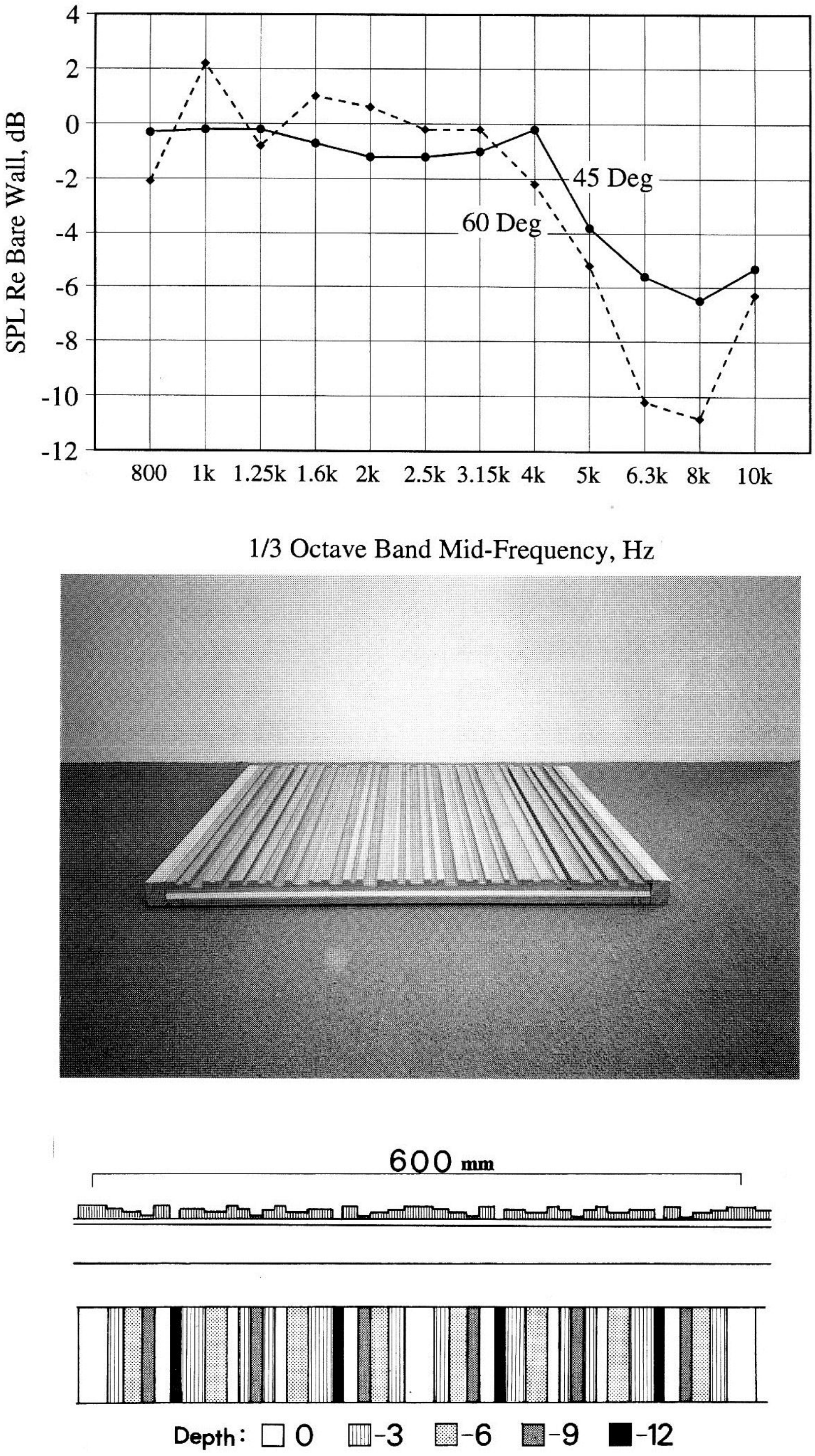


Figure B- 26 Diffusors

(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

Figure B- 27 Changes that affect absorption of membrane absorbers are shown with dashed line. First dashed line illustrates the effect of larger damping, the second dashed line shows the impact of lower mass or increased stiffness f membrane absorber.

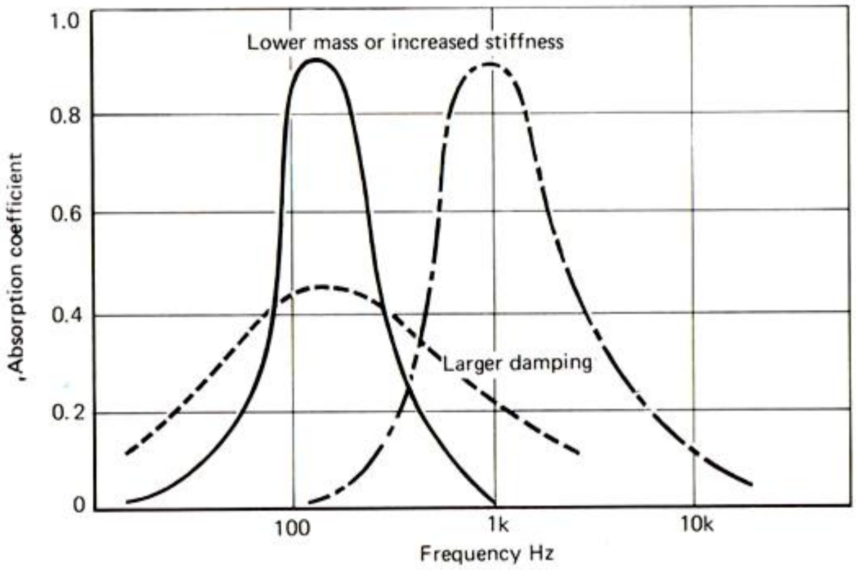


Figure B- 27 Changes that affect absorption of membrane absorbers
(Decimin Control Systems P. Ltd. ; Web Page;*Technical information*)

Figure B- 28 Effect of percentage of perforation shows significant increasing of absorption grade with rise of percentage of perforation on material.

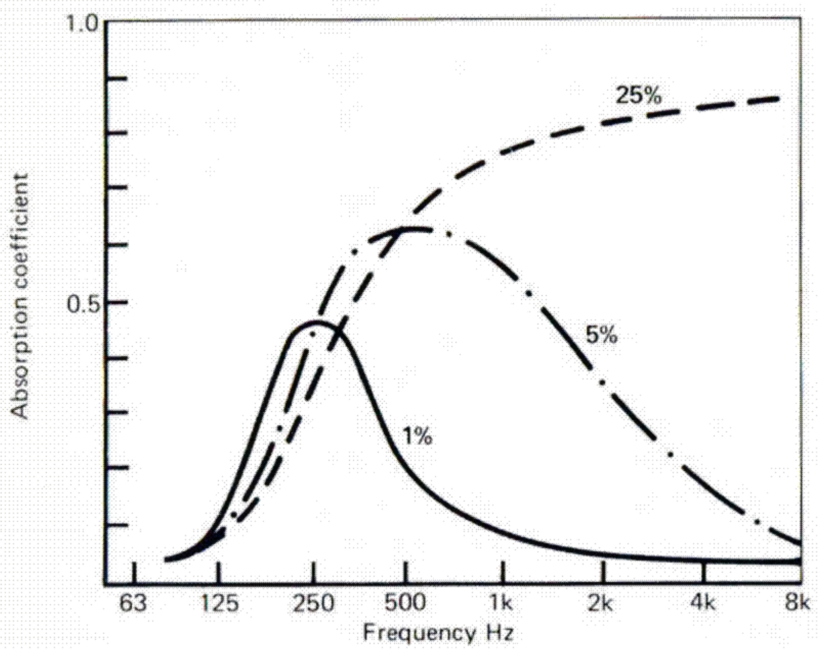


Figure B- 28 Effect of percentage of perforation
(Decimin Control Systems P. Ltd. ; Web Page;*Technical information*)

Coats of paint on the face of an absorptive material is also a question of consideration. Absorber panels should be carefully painted while oil based paint can significantly diminish the absorption coefficient. Emulsion paint which is water washable should be used for that purpose.

B 1.5.2 Air dissipation as a special type of absorption

See generally (Fasold;Book;*Scallschutz und Raumakustik in der Praxis: Planungsbeispiele und konstruktive Lösungen*; 1998.), (Meyer;Book;*Kirchenakustik*; 2003).

When talking about air dissipation the term damping is commonly used.

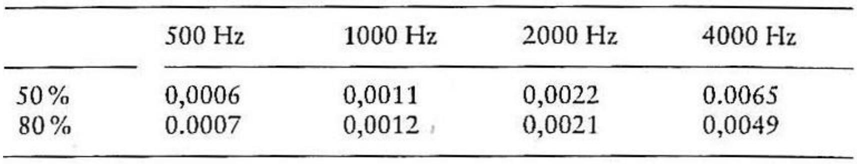
Air dissipation is related to reverberation in way that it counts in reverberation equation only in high frequencies and with great volume.

Absorption grade of air is negligible for designing purpose because values of air absorption in an open space in dB/km in frequency 125 Hz are 0.5 dB/km! and by frequency of 2000 Hz is 8 dB/km.

When calculating air absorption, we do not use coefficient α for absorption grade to multiply it with absorbing area because air could not be calculated in terms of m2. It is not possible to get absorption area A that way to put it into Sabine or other equation for getting out reverberation value. Therefore for air dissipation we use the acoustic attenuation constant m that is used in following formula for calculating equivalent absorption area: A= 4xmxV (m^2).

In a closed space the acoustic attenuation constant when temperature is 20°C for air humidity of 50% in frequency 500 Hz is 0.0006, for frequency f 200 Hz the constant is 0.0022, for frequency 400 Hz constant is 0.0065. When humidity rises to 80% the constant for frequency of 500 Hz is 0.0007 $^{m-1}$, for frequency of 2000 it is 0.0021, and for 4000 Hz the constant is 0.0049 $^{m-1}$. In this way it will be evident that for a volume of 1000 m3 for a frequency of 400 Hz we get only ca 30 m2 of equivalent absorption area. For a volume of 10 000 m3 and same frequency of 4000 Hz we get equivalent absorption grade of about 300 m2 which is respectable in this case. In fact in a cathedral of about 100 000 m3 in volume air dissipation loss will be for a reverberation of 5.7 s and a frequency of 4000 Hz about 90% of all absorption for a temperature of about 15°C and a humidity of 60%. Dissipation percentage is smaller for frequency of 1000 Hz and is only 15% of all absorption. For spaces of 15 000 m3 in volume the dissipation grade for frequency of 4000 Hz is 30% and for frequency of 1000 Hz it is only 10% of all absorption.

Figure B- 29 The attenuation constant m deppendent on air humidity of 50% or 80% and dependent also on frequency



	500 Hz	1000 Hz	2000 Hz	4000 Hz
50 %	0,0006	0,0011	0,0022	0.0065
80 %	0.0007	0,0012	0,0021	0,0049

Figure B- 29 The attenuation constant m deppendent on air humidity of 50% or 80% and dependent also on frequency

(Meyer;Book;Kirchenakustik; 2003)

So, dissipation of sound through the air is important only in open spaces or in spaces with great volumes and then also only at high frequencies.

Getting to know the absorption contributes to defining methods for high quality sound because absorption should be taken into consideration when dealing with late reflection. And conversely, reflection should be taken into consideration for early reflection and reverberant field. Absorption and reflection are the opposite sides of one coin; one can not exist without the other.

For the purpose of defining the right method of designing sound demanding spaces, it is of major importance to know the reflection grade of materials used in a space because it is the part of the equation in calculating every characteristic of sound.

Nowadays we have lot of materials which have their reflection grade values measured and the awareness of such a demand for reflection grade helps in dealing with sound. It is also important to know how to install the material in right way to obtain the best result. The construction process itself is tightly connected to sound quality and awareness of the issue is of major importance for obtaining the best result. It is the same as if one buys computer hardware, not knowing the program, in other word software and trying to get the result out of computer. In our case calculation and picking out the model and further design of a space is in fact just hardware and the handling of the material is the software. One without another will not produce a good result.

So, the methodology for achieving sound quality can be divided into two subfields; the first area is everything that is on paper and the second area is real material. In this dissertation more light will be thrown on this first, paper, area of the methodology. But, this is the time to point out that without a high quality realisation of the paper numbers it will be impossible to achieve the right result, in other words, high quality sound.

SECTION B 2 Additional definitions of sound field in room acoustics

See generally (Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.),

(Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999).

Additional definitions of sound field in room acoustics, newest criteria for designing acoustics in space are going to be discussed in this chapter. When designing a space with acoustically demanding characteristics, not only the reverberation time should be calculated. Subjective experience of room acoustics aesthetics is sculptured through criteria such as: warmth of the sound, spaciousness, clarity, resonance. Mostly reverberation criteria are used to describe the sound in one hall. Also, most commonly, reverberation is not used in its fullness because reverberation differs in different frequency heights. This latter is especially important for multifunctional places that are used for both speech and music. Mostly, acoustics in spaces are only reverberation, but not the structure of the sound field. Reverberation gives us the possibility to get inside musical feeling, but there is another part of the sound field and it is obtained through the right amount of sound to get enough intelligibility, to hear enough brilliance, to hear the correct amount of bass etc.

Contemporary acoustic analysis consists of measuring other characteristics of the sound field. Contemporary measured sound characteristics are Spaciousness, Loudness, Strength of the Sound(G), Warmth, or Bass ratio (BR) or Bass strength (Glow), Intimacy or Initial–Time-Delay-Gap, Space diffusivity index (SDI) or Acoustical glare, Definition of clarity or Early-to-late Energy Ratio or speech intelligibility, ST 1. Acoustics also considers noise level in the space.

B 2.1 Spaciousness

Spaciousness of sound comes primarily from lateral reflections in the hall, such as reflection from the sidewalls or side-balcony fronts. The degree of spaciousness ranks as one of the primary reasons why one concert hall sounds better then another. Because a listener takes sound binaurally - through two ears - the brain interprets that delay of sound and this fact is responsible for the phenomenon of spaciousness. In a hall where many reflections converge at various angles on the audience in the first 80 ms, a substantial portion of reflections will be lateral and the right difference caused by binaurality will result in a sense of spaciousness and superior acoustics. This is measured with the Binaural Quality Index. The presence of strong bass sound will also add somewhat to a hall’s spaciousness. The phenomenon of spaciousness does not exist in open spaces.

$BQI = 1\text{-}IACC_{E3}$. IACC is something that is measured in halls and is called the interaural cross correlation coefficient. E designates early sound, less than 80 ms and 3 indicates 500, 100, 2000 bands. If BQI was found to be above 0,5, and in the highest-rated halls above 0,6, indicating that in very good halls the similarity of the sound at the two ears is surprisingly low. And surprisingly, the greater the sound difference between the ears, the more it seems to us that there is a greater space and correlatively the greater the music, to our brains that means that the music is loud, which we appreciate: the effort, the energy...

BQI differs only by 10 % whether the hall is occupied or unoccupied. Spaciousness could be achieved by one of three means: 1. some combination of suspended or sine walls, splayed panels and by steps to preserve bass energy.2. Shaping of the sidewalls near the proscenium and at the sides of the performing space so as to direct the sound more uniformly to the audience area 3 interspersing seating area with walls that are located to provide lateral reflection as in surround hall. The interaural cross correlation or IACC, should be measured and signifies the relative difference between the sound that arrives at the left and right ear of a listener in first 80 ms

LEV also provides greater sense of spatial impression. It is sound energy measured in the first 80 ms. Higher values mean the higher spatial impression. LEV= early lateral energy/ total early energy.

Spaciousness could be described as the difference between feeling inside the music and looking at it as through a window.

B 2.2 Loudness, Strength of the Sound(G)

Dynamic support means both quiet support for the pianissimo parts and majestic levels at the fortissimo. Fortissimo is only possible if the hall is not too large and if there is minimum of carpets, draperies, and lack of overlay upholstered seats. For some composers, a small hall can be too loud. So, halls should not be too large, because two halls with the same reverberation sound could sound 2.5 dB different. Knowing that 10 dB doubles the loudness effect, 2.5 then means that the music was 25 percent louder in one hall comparing to another with the same reverberation time. The measurement is strength factor G.

Measuring the sound strength we get loudness. Measured with a microphone and a calibrated sound –level meter one talks about early and reverberant strength of sound. If the strength of a sound increases or decreases by about 10 dB it s loudness as one hears is doubled or halved.. A sound emitted in a hall with 1000 seats would be louder than that in a hall with 3000 or 5000 seats if both halls have the same reverberation time. But the strength of sound remains the same. Music also sounds louder in a highly reverberant hall than in dead hall. It is notable that in a hall at mid-frequencies the audience area actually absorbs up to 80 percent of the total sound radiated by orchestra. In the language of musicians strength or loudness is equal to dynamics. Loudness is formed by four architectural features:

1) the greater the distance of the listener from the stage the less loudness,
2) those surfaces that reflect early sound energy to the audience, preferably from the lateral directions, increase the loudness,
3) the larger the acoustical area S (audience +orchestra), and the larger the cubic volume, the less the loudness,
4) added materials that absorb sound, such as carpets, draperies, heavily upholstered seats, and pipe organs also reduce the loudness.

So, narrow rectangular halls are supportive for loudness. The same can be accomplished with special panels on the sidewalls or hung from the ceiling because they reflect early sound towards the listener. An example of successful augmentation of the sound level in a large wide concert hall is in the Costa Mesa (California) Segerstrom hall, where large, slanted, sound-reflecting panels are located in the upper sidewalls.

A very great part of loudness is dependent on the size of the audience. The greater the audience is, the less energy of sound comes to a single person from the same orchestra.

RELATIVE LOUDNESS (L) or RELATIVE STRENGTH (G). G is strength index in dB and it in fact represents the difference between sound source level and level in auditorium. The difference should not be greater than 3 or 5 dB. Relative loudness level also called overall strength is the sound energy level at a seat in a room compared to the sound level at 10 m from the sound source in anechoic environment. It measures the contribution to loudness of the early reflections and reverberation in the room. Relative loudness or relative strength was proposed to approximate the subjective sense of loudness:

$$G=10\log \frac{loudness\ of\ sound\ in\ room}{loudness\ in\ anechoic\ room\, at 10m}$$

Further, this is equation written as:$G=SPL-SPL_A$

where SPL…sound power level of the source,

$SPL_{A\ldots}$sound power level of the same source in condition of anechoic space measured in distance of 10 m

$SPL_A= PWL-31$ dB

To obtain quality, a music hall should be from 3 to 5 dB from center to back with condition that the ratio between occupied and unoccupied auditorium decreases the sound 1.2 to 1.5 dB.

B 2.3 Warmth, or Bass ratio (BR) or Bass strength (G_{low})

Warmth of music in a concert hall is directly related to whether the bass sounds are clearly audible when the full orchestra is playing. It is determined by strength of the bass tone, simply measured by a sound level meter at various audience seats in a hall. A hall can be sometimes dark because it has too a strong bass because high frequencies have been swallowed, absorbed by curtains, draperies, carpets etc. The hall will lack warmth if the walls or the ceiling surfaces are constructed of thin wood panelling, which absorbs low frequencies. BR is the ratio between reverberation in only occupied halls in low frequencies to those of mid frequencies.

$BR=\frac{T_{125}+T_{250}}{T_{500}+T_{1000}}$ Values that are good are bigger then 1. The other successful method is to measure absolute G_{125} in decibels. It is also called G_{low}.

B 2.4 Intimacy or Initial–Time-Delay-Gap

A hall can have acoustical intimacy if sound seem to originate from nearby surfaces, sometimes it would be said that such a hall has “presence”. Any listener first hears the direct sound which travels in a straight line from an instrument to the person’s ear. If the time difference between the direct sound and first reflection, also known as Initial-Time-Delay Gap, is short, the hall sounds intimate. In the best ranked halls in the world ITDG is 25 ms. Usually, the first reflection arrives from a side wall or a balcony front. Thus, for a low ITDG, a hall should be narrow and have near-parallel sidewalls. Hanging reflecting panels or “saw-toothed” panels along the sidewalls can be used to guide early sound to the listener and to reduce the ITDG to the 20ms region simply by means of reflecting the sound.

B 2.5 Space diffusivity index (SDI) or Acoustical glare

Acoustical glare is irritating and the way to reduce it, if necessary, is to add fine-scale irregularities on early sound reflection panels. Baroque carvings or plaster provide such an effect.

The early sound should not be too glaring or brittle. The sound should sound mellow. Reverberant sound should come from many directions, from sides, overhead and as well from the front.

Traditional halls obtain this effect with fine- scale ornamentation on lower sidewalls. On ceilings there are often coffers, beams or curved surfaces. On upper side walls there are niches, columns, irregular boxes and statues.

Diffusion must be thought of in correlation to early sound and reverberant sound.

Irregularities scatter a sound wave during each reflection, so that, after many reflections, they add a homogenizing effect to the reverberant sound. This homogenizing effect is called diffusivity of the sound field, and for surfaces themselves we say that they have. Diffusivity could be clarified through an example of cutting apples to extract juice. The apple is only the one time reflected sound and the juice is a sound of a high diffusivity index. Through this division of the sound it is clear that we get better harmonic output, because sounds of different instruments are better fused. Surface diffusivity. Sound diffusitivity index (SDI) the more and varied the surface irregularities in a hall, the better. The depth of the irregularities on the lower sidewalls can be of lesser magnitude then those on the upper walls. The irregularities on the lower walls are designed to remove acoustical glare. Those on the upper walls primarily affect the reverberation time and need to be large to cover a wide frequency range and to thoroughly homogenize the sound. No physical measurement exists for determining the optimum amount or type of irregularities; instead we rely on visual means. Haan and Fricke 1993 have devised a visual procedure for classifying surfaces based on their irregularities and they found three degrees of diffusivity as follows: HIGH DIFFUSIVITY SDI=1 For high diffusivity, the ceiling is coffered with deep recesses or beams which are greater than 10cm in depth, but not so great as to block the wave inside themselves, that is to say, no greater then about 25 cm. The upper sidewall should have random diffusing elements of sizable depth, or frequent niches and columns oriented vertically, over them. To avoid acoustical glare from early lateral reflections, the lower side walls should have fine scale diffusion of about 10 cm depth. No area should absorb sound appreciably . Medium diffusivity SDI=0, 5. Broken surfaces of varying depth on the ceiling and sidewalls, otherwise ornamentally decorative treatment applied with shallow recesses, on the upper side wall, no greater than 5 cm in depth. No absorbing surfaces as above. Low diffusivity SDI=0 Large separate panelling, or smoothly curved surfaces, or large flat and smooth surfaces, or heavy absorptive treatment applied. In that way each surface could be measured and the arithmetic mean of all the surfaces that way is determined. The pioneer of diffusion surfaces is Manfred Schroeder who in1986 made an equation for constructing diffusors. Diffusors are used to make texture of the sound and to minimize unwanted late reflection that could result in an echo, in other words, using the effect of sound wave interference one no more has to use absorptive materials. Today on the market there are diffusors that are used to control flutter echo without using absorption.

Diffusion of early sound, to reduce acoustical glare, irregularities of about 2.5 to 5 cm deep should be used in reflecting surfaces.

Diffusion of reverberant sound means giving a homogenizing effect to the reverberant sound by scattering. No physical measurement exists for determining the optimum amount or type of irregularities, instead we rely on visual means.

High diffusivity means that a ceiling has coffers or deep beams greater than 10 cm in depth but not greater than 25 cm. The upper side wall has niches and columns. Lower side walls should have irregularities 10 cm deep. No area should absorb appreciably except openings for air conditioning. Visual measurement is 1.

Medium diffusivity means surfaces of varying depth on the ceiling. On sidewalls, shallow recesses of about 5 cm in depth. No absorbing surfaces here either. Visual measurement is 0.5.

Low diffusivity means separate panelling, or smoothing curved surfaces, or large flat and smooth surfaces or heavy absorption treatment applied. Visual measurement is 0.

Surface diffusivity index SDI is obtained by dividing the total diffusing area points by actual size of ceiling and side walls. Example: Total area of ceiling is 3200 m2, 1000 m2 is smooth and the rest is coffered.0x1000 m2 +1x2200 m2= 2200 m2. Further to that 2200m2/3200m2=0.69 SDI for the ceiling.

B 2.6 Definition of clarity or Early-to-late Energy Ratio or speech intelligibility

Definition of clarity or Early-to-late Energy Ratio or speech intelligibility, synonyms for the same musical quality, names the degree to which a listener can distinguish sounds in a musical performance. Definition is discernible in two forms: horizontal, related to tones played in succession, and vertical, related to tones played simultaneously. It is a result of many factors being superimposed, both musical and acoustical.

ELR early-late ratio. ELR early-late ratio is very reliable. For speech 50 ms ratio dividing time is used and for music 80 ms time dividing is used. These measures are C50 and C80.

Early to late Energy Ratio $E1_t$ is $C_t = 10 \log \dfrac{early\ energy}{late\ energy}$

It is also called the clarity or clearness index and is denoted as C or C80. For speech the first 50 ms are used and for music the first 80 ms. However, C80 has been found to be significantly correlated with EDT $_{10}$.

The composer can specify certain musical factors that determine the horizontal definition, such as tempo, repetition and numbers of tones in a phrase, and the relative loudness of successive tones. Horizontal definition increases both as the length of the reverberation time decreases and as the ratio of the loudness of the early sound to that of the reverberant sound increases. If the definition, it is expressed in DB, is a positive quantity, the early sound dominates. If negative, the strength of reverberant sound dominates. If zero, they are alike.

Clarity decreases with increased reverberation and vice versa. In physical measurements it is the ratio of the energy in the early sound to that in the reverberant sound, a ratio that is expressed in dB by C_{80}. If there is no reverberation – if the room is very dead - the music will be very clear and C_{80} will have a large positive value in decibels. If the reverberation time is very large - such as that which exists in huge cathedrals - the music will be unclear and C_{80} will take on a large negative dB value. C_{80} equals 0 dB when the early energy is equal to the reverberant energy.

Different amounts of clarity are desirable in different situations. During rehearsals a conductor is satisfied with a hall unoccupied and C_{80} of +1 to +5 dB, but at a concert the same conductor would be satisfied with more reverberant space and C_{80} of -1 to-4dB.. C80 in a normal music hall is so highly correlated, inversely, with the reverberant time that it cannot be used as an additional way to estimate the acoustical quality of a concert hall.

This is shown in Figure B- 30 Clarity values for speech and music

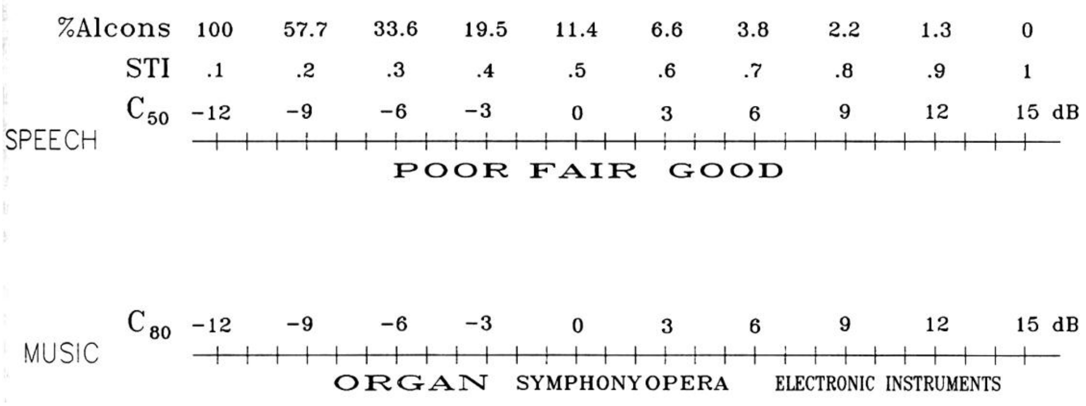


Figure B- 30 Clarity values for speech and music

(Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999)

Horizontal clarity definition means the definition of tones played in succession. Horizontal definition is best preserved when reverberant time decreases and when the loudness of early sound increases the reverberant sound.

Vertical definition refers to the degree to which notes that sound simultaneously are heard separately. Performers can alter the vertical definition by varying the dynamics of their sounds. The performance space shapes vertical definition also by acoustical factors so that it balances among sound heard by audience at low, middle and high frequencies, and the ratio of the energy in the early sound to that in the reverberant sound.

For instance, Gregorian chant is best performed with little horizontal definition, preferably in cathedral-like rooms with a very a long reverberation time and lots of reverberant energy compared to the early sound energy. At the other end of the spectrum, a piano concerto by Mozart - with its rapid solo passages and the delicate interplay of piano and different orchestral voices - needs considerable horizontal and vertical definition. It should be performed in a room that has a relatively short reverberation time and that allows for a large amount of energy in the early sound relative to that in the reverberant. It means that you can hear the best of Mozart’s music when you are sitting close to orchestra because his style of music sounds best at a location where the amount of early energy exceeds that of reverberant energy.

A number of objective measures have been developed for rating clarity. Some of these measures are STI, the speech transmission index, its derivation rapid STI=RASTI, %Alcons, the articulation loss of consonants. Early sound reflections are useful as they increase the loudness of the sound thus increasing intelligibility. Later arriving sounds from late arriving reflection, reverberation and background noise decrease the intelligibility. Measurement for speech intelligibility is STI Speech transmission index and RASTI rapid speech transmission index. STI is an acoustical measurement that relates the levels of the direct sound and early reflections to the reverberant sound and background noise for a speech.

STI is thought to account for the relative degradation of speech by the combination of background noise, reverberation and distance. Values range from ideal 1.0 to 0.0. Rooms with STI above 0.75 are thought to provide for good intelligibility and under 0.45 poor to bad intelligibility.

B 2.7 ST 1

ST1 is the degree of stage support. SD 1 measures how well a player hears himself and other players near him on stage. It is the degree of support that a hall gives to players on stage, owing to reflection of the sound from the walls and ceiling of the hall and of the enclosure. It is measured, in dB , between the impulse sound energy that arrives at a player’s position within first 10 ms, measured 1 m from the sound source, and that which arrives in time interval between 20 to 100 ms at the same position. The measurements are made on stage without musicians but with instruments and chairs. The measurement is taken on several positions on stage and the data are averaged. When a canopy is used to create favourable ST 1, its height should be between 7 to 13 m. In that case ST 1 equals approximately -12 dB to -15 dB. Generally speaking, halls with a high ceiling and no canopy make it more difficult for an orchestra to play good ensemble.

B 2.8 Other qualities of the sound

1) Timbre and Tone colour. The commonly quoted American National Standards Institute formal definition of timbre reflects this: 'Timbre is that attribute of auditory sensation in

terms of which a listener can judge two sounds similarly presented and having the same loudness and pitch as being dissimilar' (ANSI, 1960). In other words, two sounds that are perceived as being different but which have the same perceived loudness and pitch differ by virtue of their timbre. The timbre of a note is the aspect by which a listener recognizes the instrument which is playing a note when, for example, instruments play notes with the same pitch, loudness and duration. It is the quality that distinguishes one instrument from another or one voice from another. Tone colour describes the balance between the strengths of low, middle and high frequencies. The hall can amplified to the brittleness or muffle of a sound with for instance main ceiling directing certain sound to some part of the hall. Treble Ratio based on early decay time, TR (EDT) is a measurement proposed to evaluate timber or tonal balance, especially brilliance. It is measure similar to base ratio but it refers on higher frequency ranges. TR(RT)= $\frac{T_{500}+T_{1000}}{T_{2000}+T_{4000}}$

2) Lateral fraction (LF), which equals the ratio of the energy in lateral reflections to the total energy arriving at a seat in a hall, is proved to be poorer specifier of acoustics in halls than Binaural Quality Index. Therefore, BQI is a superior measure for estimating the acoustical quality of spaciousness of a concert hall.

3) Listener Envelopment Refers to the degree to which the reverberant sound seems to surround the listener. It is the better that the sound comes from all directions rather than from for example the front direction. It is the best that the sound wave has the freedom to circulate. For this purpose diffusive sound field will serve great. That is the best accomplished with ornamentation of sidewalls, ceiling, and balcony fronts because this helps sound to spread and reflect.

4) Liveness or reverberation at mid-frequencies. Liveness corresponds generally to the 'reverberation time at the frequencies between 350 and 1400 Hz because the person/s ear is more sensitive in that region (measurements up and down)

5) Brilliance is the energy of high-frequency waves. It refers to a bright, clear, ringing sound, rich in harmonics. A lack of brilliance arises with the presence of carpets, draperies, and amount of absorbing materials. in an example where we have a hall dimensions 24.5 m in both direction the sound that travels 344 m/s, a wave would stick a wall, ceiling, or the audience about 30 times in 2 screech time a wave is reflected from a wall or a ceiling, a small amount is absorbed. Of course, the wave strikes the audience area some of the times and those areas are responsible for about 80 percent of all absorbed energy of the direct sound. But the energy of the wave is lost in air itself as a wave travels through it. The diminution of the sound because of the air is caused only in higher frequencies than 2000 HZ. The loss is greater in dry air than in humid air. So in occupied halls strict control of desirable dry air should be maintained in order not to experience loss of brilliance. Carpets should be used only in passages, draperies should be avoided. Acoustical sound absorbing materials should only be used when necessary to eliminate echoes or acoustical glare and then in areas as small as possible

6) Balance between orchestra and vocal interpreters. In architecture this is achieved with the early reflective surfaces provided near the stage to assist the singer's voice, the pit design. Good balance means that no instrumental group dominates to another and that good correlation is established between vocalist and the orchestra.

7) Immediacy of response or attack means that the hall is immediately responsive to a note. If the reflection is too long, then it seems like an echo. Conversely, if the musicians hear reflections only from the nearby surrounding stage walls, they will have no sense of a hall's acoustics.

8) Texture, high quality texture requires a large number of early reflections, uniformly but not precisely spaced apart, allowing no one to dominate. Texture is the subjective impression that listeners derive from the patterns in which the sequence of early sound reflections arrives at their ears. In an excellent hall, those reflections that arrive soon after the direct sound follow in a more or less uniform sequence. In worse halls there may be a considerable interval between the first and the following reflections or one reflection may overly dominate. Good texture requires a large number of early reflections, reasonably strong in amplitude, uniformly but not precisely spaced apart, and with no single reflection dominating the other, which is gained through relief texture of reflective areas.That is a sound parameter that is difficult to measure. It consists of the number and nature of the early sound reflection, those that arrive at listeners' ears soon after the direct sound. Even when all other parameters are acceptably near optimum, unsatisfactory texture may create remarks as the music is missing something. For good texture not only ITDG, Initial time delay gap should be short, but the reflections before the 80 ms marker should be large in number and relatively uniformly spaced.

9) Distinctness(Deutlichkeit) ratio, D., is the ratio of the sound in the first 50 ms after arrival of the direct sound to the total sound arriving. It is usually expressed as a percentage.

10) Detriments to tonal quality also should be avoided. The tone should not get for example a metallic sound if the tone is reflected by a metal fence. It is avoided by fine-scale irregularities. An also, the listener hearing a sound emanating from the surface that is reflecting sound of the original orchestra place should be avoided.

11) Uniformity of sound in audience areas should be achieved. This means that we have diffuse a sound field. In lots of halls the lack of sound is a feature under a deep overhanging balcony or at the sides of the front roads in the hall

12) From the viewpoint of this thesis concerning whether a methodology could be defined to obtain superb sound these additional criteria have significantly improved the methodology itself. There could be no methodology if we did not have a clear requirement as to what we are expecting and want to get as a result. So, these more contemporary criteria contribute to the definition of what we are looking for. Now, we are closer to answering what quality sound is and what the elements that it consists of are. This means that these additional criteria have segmented the term of quality sound into portions that can be one by one determined and calculated. But, here also stand the questions how many more criteria are going to be found in this whole picture that is called quality sound. The more

elements we determine the less we are influenced by the unknown “feeling” that the sound is of high quality. Maybe as a result we are no more going to worship historical theatres because of the historical atmosphere and the feeling that we live the history itself when listening to historical music in such a historical space. Maybe this historical splendor of past times is a criterion that could be measured as well. In other words, there could well be more criteria that are going to be found in this image of sound field. For the purpose of the thesis it is necessary to have limited amount of criteria to obtain the definite method. But, contemporary praxis shows that some criteria are major and others contribute in a smaller amount. Major criteria are calculated and the minor are then skipped. So, the method itself could not be accurate if all variables are not used. As I pointed out, some criteria could be found in the future and in addition criteria that are known today are not used to their maximal capacity could become more important. This is a question to be answered in the evolution of the science of sound for the determination of the borders of quality sound. What are the criteria that should be used, in what percentages will these criteria be used in order to get a result that is going to be appreciated as quality sound? This limit should never be determined in a hard and fast way because sound is an element of art and creativity and the limit, or in the other words, the definition, of quality sound should always stay open so that humankind could seek for, get inspired by the unknown and develop and grow in a spiritual sense.

SECTION B 3 Unwanted criteria but should be concerned in acoustical designing

B 3.1 Natural noise floor

See generally (Scribd; Web Page;*IT Dictionary*), (Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999).

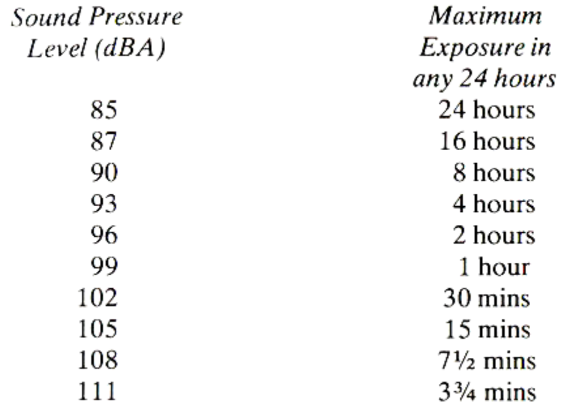
White noise is a sound that contains every frequency within the range of human hearing (generally from 20 hertz to 20 kHz) in equal amounts. Most people perceive this sound as having more high-frequency content then low, but this is not the case. This perception occurs because each successive octave has twice as many frequencies as the one preceding it. For example, from 100 Hz to 200 Hz, there are one hundred discrete frequencies. In the next octave (from 200 Hz to 400 Hz), there are two hundred frequencies.

White noise can be generated on a sound synthesizer. Sound designers can use this sound, with some processing and filtering, to create a multitude of effects such as wind, surf, space whooshes, and rumbles.

Pink noise is a variant of white noise. Pink noise is white noise that has been filtered to reduce the volume at each octave. This is done to compensate for the increase in the number of frequencies per octave. Each octave is reduced by 6 decibels, resulting in a noise sound wave that has equal energy at every octave.

Harmful sound is part of building acoustics that should be inspected and if necessary, calculated for every project.

It is very important to know that noise can harm persons hearing it if they are exposed as shown in Figure B- 31 Time exposure to dB level



Sound Pressure Level (dBA)	*Maximum Exposure in any 24 hours*
85	24 hours
87	16 hours
90	8 hours
93	4 hours
96	2 hours
99	1 hour
102	30 mins
105	15 mins
108	7½ mins
111	3¾ mins

Figure B- 31 Time exposure to dB level

(Decimin Control Systems P. Ltd. ; Web Page;*Technical information*)

The natural noise floor of the hall should be at least 20 to 30 dB quieter then the sound level during performance. Noise should be therefore something between 30 or 40 dB. Generally, the ambient noise levels for an empty good auditorium would be about 25 to 30 dB When the audience is in the hall the noise level is about 35 dB. Dynamic range of a speaker is between 45 and 85 dB. Early reflection should be in the range of 60 dB to provide good speech reinforcement.

Figure B- 32 A good signal to reverb noise is 10 dB, a good signal to background noise is 20 dB: this is the synopsis of general rules for background noise.

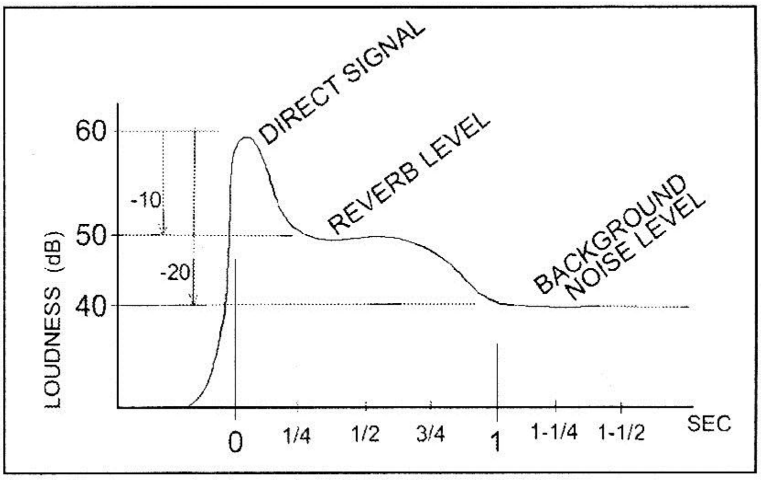


Figure B- 32 A good signal to reverb noise is 10 dB, a good signal to background noise is 20 dB (Noxon;Web Page;*Auditorium Acoustics 101,102,103,104*; 2002)

Noise level in the hall should be less than the NCB-20 criterion and preferably less than NCB-15. If the hall is located over a railway or subway line or adjacent to heavy street traffic, the hall proper may have to be vibration-insulated using springs or elastic layers in the foundation, depending on the magnitude of the vibrations. We distinguish two groups of noise and they are background noise and architectural noise. Background noise contains: floor noise when the hall is occupied, the sound of the auditorium when auditors are concentrated on performance. This means physiological sounds of a large group of people, and, particularly, breathing, turning around, moving on the chair. The phenomenon is known that people in large groups as in the case of listening to a concert act more considerately and carefully and quieter than for instance a small group of people celebrating someone’s birthday In this group of background noise there are also sound from the light and installation system: electricity, water, vents and the noise from the outside. To illustrate, a person trying to stand absolutely still, breathing as shallowly as possible still generates enough noise to register 20 dB at a distance of 3 m. There is a symbiotic effect of background noise. When the background noise is at an elevated level, people feel that they can make a little noise and no one will notice. A hall whose background noise level starts in the low 20 dB range stays quiet when the audience arrives. The other noise group is acoustic noise and in this group are: echoes and other unwanted reflections, unwanted parts of reverberation which are described in the chapter discussing unwanted late reflection.

Annoyance: as the loudness of disturbing sound is increased, people are generally more annoyed. However, presence of some persistent annoying sound at low level can cause severe annoyance, such as water dripping from a faucet. Annoyance is generally proportional to the duration of disturbing sound.

B 3.2 Dissipation through the air

Dissipation losses are different for every medium, for instance: concrete, wood. But, also we have to have in mind losses through the air. Dissipation losses in air are significant only in higher frequencies, as explained in one of the preceding chapters.

These dissipation losses in air are measurements that should be added to the total alpha amount of the whole space absorption. The constant only has an influence in spaces with great distances. The basics of dissipation are given in the chapter entitled “particle velocity and speed of sound”.

Unwanted criteria are just another side of the same problem of defining quality sound, as discussed in the chapters on additional criteria. Frequently, when a problem can not be solved, the only way to start dealing with problem is to define what the term or the problem is not. For the purpose of defining proper methodology, one way to search for the answer is to look for unwanted criteria. This attempt is maybe more indefinite then searching for the right criteria. But if we concluded that the criteria of quality sound are indefinite, then unwanted criteria could not be more indefinite then the right criteria. So, unwanted criteria are a legitimate position to go to. As seen in additional criteria observations, there are definite criteria in unwanted fields in real contemporary calculations. The limits of wanted and unwanted criteria make the calculation itself possible. But, as a result, we cannot expect perfect sound, rather the sound of the perfection we would like to hear.

SECTION B 4 Conclusion to Part B

Part B is a further investigation of what are really countable data in contemporary methods of superior sound acquisition. In this part it is all about acoustics as a science and data or in other word characteristics of sound that are presented and explored in that science.

In this part, B, it has become evident that defining the right method for gaining quality sound is not yet determined. The question is whether the method itself is ever going to be definitive because of the many questions that have stayed unsolved, and the many questions unanswered in this part.

It begins with exploring the historically oldest characteristic of sound, which is reverberation. After that, other qualities of sound are introduced like sound spaciousness, loudness, warmth, intimacy, clarity.

The ultimate goal for quality sound should be then getting as close as possible to direct sound. Today we do have definition of quality sound and it is determined by certain criteria. In the future it is possible that the definition itself is going to be improved with other criteria and unwanted criteria and the border of perception of quality sound could be quite different. Today's definition of quality sound balances between direct sound characteristics and the reverberant sensational part of sound characteristics.

The great revelation of Part B is the more reflection, the better result. In this Part it is proved that reflection is the element that is taking contemporary acoustic methods on the right trail and that it is in the future going to remain on that right trail. Reflection is the thing that has contributed to sound quality in the past and will also in the future. Reflection is in fact the axiom for acoustic methods. Even though calculations in time improved themselves and are probably going to be more accurate, reflection is always the foundation.

The answer as to whether a contemporary method could be developed for gaining superior acoustics lies in reflection as the foundation of acoustical methodology.

Other terms were investigated in Part B as well: human physical limits are helping when determining a methodology for quality sound. This is evident for instance in hearing early and late reflections. Further problem is in calculations that are on paper and then part of another phase, that of embodying and installing these numbers into materials in real time and space. Also, in this part the question has been asked whether an infinite number of criteria could and should be numbered.

PART C Methodology in Architectural Acoustics

SECTION C 1 Introduction to acoustic design methodology

To be able to design a space capable of supporting all the qualities of performed music or presentations, or any kind of performance, it is necessary to be familiar with the basic methods of how to create such a space. The details of how to obtain excellent sound characteristics can be left to acoustic consultants and collaborators from the field of acoustics, but the architect designer should know enough of the subject as to be able to ask to have some of characteristics fulfilled and achieved at every moment of the project task. This section explains elements that, in a wider sense, form the conditions for dealing with designing acoustically demanding spaces. At the outset of research into these elements, the ideas of room acoustics as comprehended by listener, musician and architect will be addressed.

C 1.1 Room acoustic terms as experienced by listeners, musicians and architects

See generally (Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.).

Whether we are professionally concerned with problems of sound or simply enjoy listening to music, we all derive information from sound. Primarily, then, we all are listeners. In that sense it is logical to start our research into sound and acoustics by understanding the listener and his or her expectations.

When we are talking to each other, face to face the amount of information that we get from hearing sound is not as great as it is in communication that is based on collective listening to speech, to music, etc. When we speak in close communication, only about 7 percent of the information is verbal (words only) and 38 percent is vocal (including tone of voice, articulation, accentuation, inflection, and other sounds) and 55 percent nonverbal. Thus a full 93 percent of message we have heard is in the other person’s tone, accentuation, and body language. When we are collective listeners then we cannot see that much of a person’s attitude, subtle body talk in his or her face and bodily posture. Listening collectively, we collect more information from the sound than we get in the case of close communicating.

Singers and actors are trained to focus on the sound they articulate so that they can be heard from larger group of listeners and not only to give their emotion through the expression of the face and body but through the dynamics of the voice. The fact is that we understand better, or get more precise information when listening in real time terms and in the same space with speaker, actor or musician. The feeling is better than listening to a tape recording of a situation. On tape, the body language component is not involved. Opera singers are trained to carry the meaning and the feeling of the composer through musical phrasing and to minimize body language. With training, in this way they significantly augment the volume of their voice

Figure C- 1 Sound levels of music illustrates what levels of particular performance can be obtained.

Sound levels of music	
Normal piano practice	60 -70dB
Fortissimo Singer, 3'	70dB
Chamber music, small auditorium	75 - 85dB
Piano Fortissimo	84 - 103dB
Violin	82 - 92dB
Cello	85 -111dB
Oboe	95-112dB
Flute	92 -103dB
Piccolo	90 -106dB
Clarinet	85 - 114dB
French horn	90 - 106dB
Trombone	85 - 114dB
Tympani & bass drum	106dB
Walkman on 5/10	94dB
Symphonic music peak	120 - 137dB
Amplifier rock, 4-6'	120dB
Rock music peak	150dB

Figure C- 1 Sound levels of music

(Galen Carol Audio; Web Page;*Decibel (Loudness) Comparison Chart*)

It also should be pointed out that one-third of the total power of a 75-piece orchestra comes from the bass drum. Also for better understanding it should be said that the uppermost octave of the piccolo is 2,048-4,096 Hz. High frequency sounds of 2-4,000 Hz cause the most damage to hearing.

Listeners, which means everybody participating in the domain of sound as producers or receivers, are agreed that sound should be heard in all its dynamic range, whether it is quiet or loud.

Here are characteristics of music that need to be conveyed in a high quality manner.(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

"it must be so quiet that the very soft (pp) passages are clearly audible. It must have reverberation time long enough to carry the crescendos to dramatic very loud (ff) climaxes. The music must be sufficiently clear that rapidly moving violin passages do not melt into a general "glob". The hall should have a spacious sound, making the music full and rich and apparently much "larger" than the instrument from which it emanates. It must endow the music with a pleasant "texture", an indescribable, but hearable, quantity that can be demonstrated by electronic measurements. The bass sound of the orchestra must have the "power" to provide a solid foundation to the music. Finally, there should be no echoes. After that, also there should be no "source shifts"; that is to say, all or part of the orchestra should not seem to originate at some side or ceiling surface." Listeners' impressions are built through multiple elements: architecture, composition, conductor, performers etc"

Critics are professional listeners. Here are some of the questions that should be asked when writing a review about the performance of some piece: Are the tonal qualities of and the balance among the different sections of the orchestra to my liking? Is the sound as good as or better than that in the hall that I regularly attend? Is the hall overlay bright or reverberant or too clinical or dry? Did the principal piece sound as good as the best performance of that composition that I have ever heard? If not, was the orchestra at fault or the acoustics? Were there any echoes or disturbing sound reflections? Was there any acoustic distortion? It should be highlighted here that critics' opinion about a piece can significantly contribute to the reputation of a concert hall. One concert hall's acquisition of a reputation of being better than another is bound to involve: excellent acoustical features and a number of famous interpreters. It is the same with opinions of world-famous interpreters and conductors about a specific concert hall. HIDAKA & Baranek, 2000the survey obtained responses from 21 well-known opera conductors.The questionnaires contained a rating scale for each house, with the option "Poor" and "One of the Best" at two extremes and "Passable", "Good", and "Very Good" in between. The Buenos Aires Opera Colon is at the top and the very large Tokyo NHK Hall at the bottom.

Figure C- 2 Teatro Colon, Buenos Aires, Argentina inside view and Figure C- 3 Teatro Colon, Buenos Aires, Argentina, plan and section are following:

Figure C- 2 Teatro Colon, Buenos Aires, Argentina inside view

(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

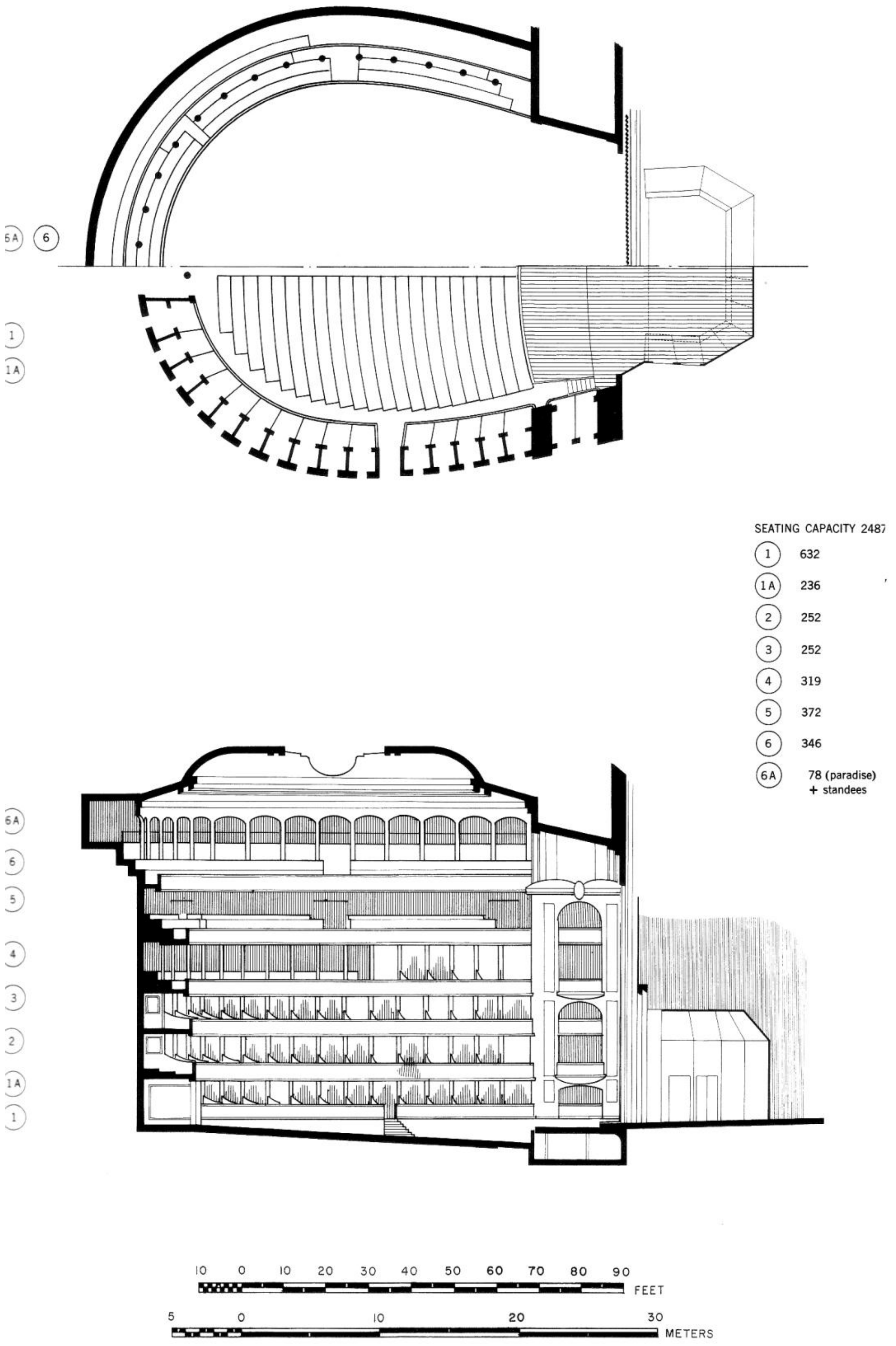


Figure C- 3 Teatro Colon, Buenos Aires, Argentina, plan and section

(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

The reverberation time of the best six opera houses ranged from 1.24 s, Milan, La Scala to 1.6 s, Dresden, Semperoper, with a mean value for all of 1.4 s. The best seated less than 2500 persons, and thus were not too wide, creating a sense of “intimacy“, which is provided only if there are sound-reflecting surfaces near the proscenium... In the best houses, the singer’s voice was judged as “clearer” than the sound of the orchestra. In only three houses, Munich, Prague and New York, was the sound in the pit, the conductor’s position, judged significantly better than the sound in the audience.

On the other hand, the musician has to deal with how to produce music capable of reaching the listener. Clearly, then, the same music piece is not going to be interpreted the same way in different spaces. This is mainly in the hands of the conductor. It is known that some famous music pieces were written for a particular church, for instance Bach for the Lutheran Thomaskirche in Leipzig, and classical composers wrote symphonies for defined theatres. Today, all these pieces are put on in different halls all around the world and the conductor is the one who will know how to interpret the piece of music in the specific conditions.

For instance, Herbert von Karajan, music director of Berlin Philharmonic Orchestra, the Vienna Philharmonic, the Vienna Staaatsoper was very important in spreading support for the new type of acoustic design.: “Of all the designs submitted one [by Architect Hans Scharoun] seems to stand out above others; it is founded on the principle that the performers should be in the middle... It seems to me... that this arrangement with the orchestra centrally placed will be better suited than any known hall to the musical style of the Berlin Philharmonic”. Von Karajan thus gave an initiative to a new design for grand halls. An experiment was performed by students of acoustics in Harvard, in which they followed the work of two conductors, Koussevitzky and Stokowsky. Both of the conductors claimed that the hall in which his particular orchestra performed was acoustically better. The conclusion of the research was that they both accommodated to the conditions of the space in which they performed the most and that they had to put in I more of an effort to obtain adequate sound excellence in other halls. James De Preist, music director of the Oregon Symphony wrote: “Every concert hall has its individual acoustics, which demand different adjustments and accommodation of the orchestra that plays there. The conductor in particular develops the performance of a composition in accordance with those acoustics, adjusting tempo, dynamics, structural spacing - to fashion and interpretation. The Academy of Music … with its dry acoustics (short reverberation time) that absorbs and even chokes sound, impedes leisurely tempi and long soaring lines. In response, the orchestra’s conductor has required endless bowing arms from the players and directed them to attack and sustain notes in order to make them “sing”. That effort to compensate for the dryness of the hall, of course, had produced the orchestra’s trademark opulence- its rich blending sonorities...in Carnegie Hall I could encourage the softest pianissimo and allow the hall to play a role in sustaining the notes. Although the adjustment was quite subtle- really a matter of recalibrating dynamics...” When speaking of individual performers pianists most like spaces that have a shorter reverberation time, more than do performers on other instruments. This is partly because piano players have the pedal for prolonging the duration of the note. The music for organs is rather dependent on reverberation. The same way, violinists want a longer reverberation time, as Isaac Stern has figuratively explained: “Reverberation is of a great help to a violinist. As he goes from one note to another the previous note is preserved and he has the feeling that each note is surrounded by strength. When this happens, the violinist does not feel that his playing is bare or “naked”; there is a friendly aura surrounding each note. You want to hear clearly in a hall, but there should also be this desirable blending of the sound. If each successive note blends into the previous sound, it gives the violinist sound to work with. The resulting effect is very flattering. It is like walking with jet-assisted takeoff.

When asking these questions about listeners and musicians and critics in the light of answering whether a single methodology for the quality of sound could be developed then the first obstacle is the word feeling. The more feeling is mentioned, the less responsible the science of sound is. The science of sound is established on criteria of quality of sound and where there is no criterion to define quality of sound then the word “feeling” will arise. When wanting to gradate “feeling” impact on sound quality then listeners are the most in the “feeling” area, then come musicians, after them critics, after them architects while least influenced by mere feeling are acousticians. With a true methodology, feeling should be turned off completely. It should be obligatory to determine the criteria that make for high quality music instead of sensing whether it feels good to hear the quality of sound. However, it must be left to the future to see whether it is going to be possible to know all the criteria that make for quality sound. At this moment all efforts to achieve the best sound results are subject to the question: “how do we feel when hearing the sound?” And in almost every case the sound image is influenced by other inputs such as the interior decoration, whether we are in pleasant company, the theme that is being presented etc. The perception of high sound quality is influenced by all these factors. And the paradox goes further for when you can turn off more disturbing factors in order to hear only the sound quality then it means that you are not enjoying the sound.

SECTION C 2 A historical retrospect _From outdoor to indoor acoustics

C 2.1 Outdoor acoustics

See generally (Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999).

The transmission of sound in a free-space environment involves a diminution of sound intensity by 6 dB, or 25%, of its intensity for every doubling of distance. The way sound changes with distance from the source is, however, dependent on the size and shape of the source and also on the surrounding environment and prevailing air currents. It is relatively simple to calculate provided the source is small and outdoors, but indoor calculations (in a reverberant field) are rather more complex.

The sound level in a free field or an open space decreases by 6 dB as the distance from the source is doubled. The equation is called the inverse square law. For instance, if at 20 m from the source the sound level is reduced by 6 dB, then at 40 m from the source the sound level will be 12 dB lower than the original sound.

C 2.2 Transition to indoor acoustics

If a ceiling is added to an open space theatre the reflection will be heard shortly after the direct sound and it will increase the overall sound level. If a ceiling is designed to provide three or more reflections arriving shortly after the direct sound in the rear of the room, the sound level will be increased there as well, even though the direct sound has been decreased due to distance. This helps to maintain even sound levels throughout the entire room.

Figure C- 4 An office that is partly open-plan does not provide sound insulation

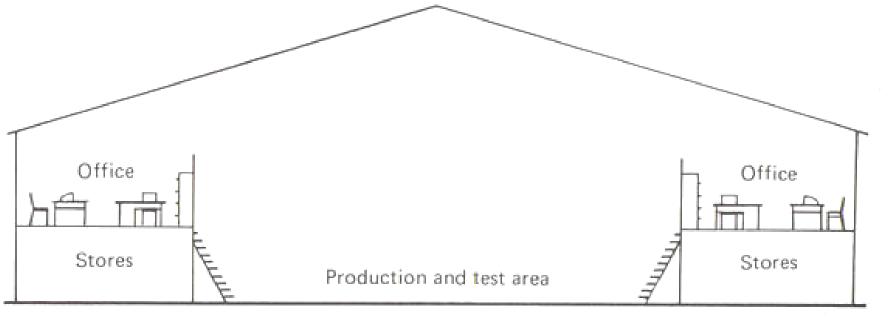


Figure C- 4 An office that is partly open-plan does not provide sound insulation (Decimin Control Systems P. Ltd. ; Web Page;*Technical information*)

The further we are from the source, the more the number of reflecting areas on ceiling and side walls has to be augmented to get sound levels or loudness as equal as possible.

The height of the ceiling will to be calculated from the distance that sound has to pass in the first 80 msec knowing that the speed of the sound is 330 m/s. Out of this we get as a result that the ceiling should not be more than 11.5 m, or, preferably, somewhere between 8 and 13 m.

Historically, structurally and even design-wise, after the canopy evolved performance places became indoor places because to the canopy walls and ceiling were added. This is the shell that envelops the audience, providing additional reinforcement by reflected sound energy. The shaping of walls and ceiling assists both clarity and loudness, but sound-reflecting surfaces can also impair clarity by creating unwanted effects such as too many echoes, flutter (rapidly repeating echoes), focusing and too loud or too long reverberations. Comparing indoor performances with outdoor the conclusion is that indoors the hearing conditions are improved but also provide a potential for numerous problems. In searching for a methodology to produce high quality sound there is the question of what type of sound we expect to get with quality sound. The definition of high quality sound is still not unambiguous and as the science of sound is still evolving, the definition of quality sound is becoming more precise. One still indefinite element is whether high quality sound is more like a sound hard from a distance of 1 m or 10 m or more. What is the preferred distance involved in discussion of high quality sound? Also, one unlimited variable is whether the preferred high quality sound is in open space where there is no reflection, only the direct sound, or in a closed space where reflection occurs.

SECTION C 3 A historical retrospect_Reverberation time through history

Throughout history, in a composer's work significant changes have arisen in the field of requirements related to architecture acoustics.

In prior centuries, and well on into the 20th century, acoustics were largely matter of happy circumstances or the result of reproducing a building with known characteristics, the practice of the Viennese architects Ferdinand Fellner and Herman Helmer, authors of approximately forty theatres in central Europe in the end of the 19th century.

Historically, the monumental architecture of churches produced an excellent acoustic character for music liturgy but not as successfully for spoken liturgy; these characteristics had a profound influence on the early development of music. In an analogous history, secular music developed in palace ballrooms and courtyard theaters. After that, secular music took the lead and further developed into the mainstream in operas. In these times the dominant influences on performance places were construction methods, the esthetics of the time and the ability for patrons to see and to be seen.

C 3.1 Greeks and Romans

See generally (Jacobsen;Web Page;*Acoustic technology, Annual Report 2006*; 2007).

GREEK and ROMAN theatres addressed this problem by arranging the audience in a steeply tiered fashion and by arranging them as close to the performance as possible, reducing the distance sound was required to travel and ensuring direct line of sight transmission from the performers to all members of the audience without much audience absorption. These two measures contributed to the acoustical success of these theatres.

A third contributing factor was the location of the theater at quiet sites. Late afternoon performances required sites with setting sun behind the audience, with precautions about the wind direction and sound refraction towards the audience. In the Roman theatres in particular a wall behind performers was added to the direct sound, and the reflected energy coming to the listener's ears in less than 30 ms after the direct sound reinforced the direct sound in both loudness and clarity. These sound-reflecting walls may be thought of as an early first step toward room acoustics. Subsequent evolution came in the design of ceiling and wall surfaces of concert wall, opera houses.

C 3.2 Mediaeval acoustics

See generally (W.W.Norton; Web Page;*Essentaials of Music*).

From year 450 to 1450. This era begins with the fall of the Roman Empire and ends in approximately the middle of the fifteenth century, establishing the end of the Middle Ages and the beginning of the Renaissance. Although this is very long period, music developed in small terms and in a homogeneous or monophonic direction the whole of that 1000 year period.

Since creating musical manuscripts was very expensive, due to the expense of parchment, and the huge amount of time necessary for a scribe to copy it all down, only wealthy institutions were able to create manuscripts which have survived to the present time. Chant (or plainsong) is a monophonic sacred form which represents the earliest known music of the Christian church. Around the end of the ninth century, singers in monasteries such as St. Gall in Switzerland began experimenting with adding another part to the chant, generally a voice in parallel motion, singing in mostly perfect fourths or fifths with the original tune. This development is called organum, and represents the beginnings of harmony and, ultimately, counterpoint. Over the next several centuries organum developed in several ways. The music of the troubadours and trouvères was a vernacular tradition of monophonic secular song, probably accompanied by instruments, sung by professional, occasionally itinerant, musicians who were as skilled poets as they were singers and instrumentalists. The closed spaces of that historical period are the Early Christian churches and after that the Gothic cathedrals. Secular music was held in open spaces or in the privacy of ballrooms of feudal lords.

The reverberation time in Gothic cathedrals was very long, the longer the more voluminous the church is. This reverberation time is therefore from 2 s to 11 s.

In secular music the reverberation time is short due to the mostly recitative kind of music that needed understanding.

C 3.3 Renaissance acoustics

Renaissance music is European music written during the Renaissance, approximately 1400 - 1600. The Renaissance is in fact the Italian humanist movement that rediscovered and reinterpreted the aesthetics of ancient Greece and Rome; it also influenced the development of musical style during the period.

Common sacred genres were the mass, the motet, the *madrigale spirituale*, and the laude.

Palestrina came to cultivate a freely flowing style of counterpoint in a thick, rich texture within which consonance followed dissonance on a nearly beat-by-beat basis.

Secular vocal genres included the madrigal, the *frottola*, the *caccia*, the chanson in several forms. Purely instrumental music included consort music for recorder or viol and other instruments, and dances for various ensembles. Common instrumental genres were the toccata, the prelude, the ricercar, the canzona, and intabulation. Instrumental ensembles for dances might play a basse danse (or bassedanza), a pavane, a galliard, an allemande, or a courante.

Characteristic of music were: melodies with balanced phrases, harmonies that use full triads, vocal forms tied to structure of texts, dances based on simple binary forms. The most significant composers of the period were: Guillaume Du Fay,Josquin Desprez , Giovanni Pierluigi da Palestrina , John Farmer and Claudio Monteverdi . Middle Ages and Renaissance music often took place in spaces called oratories, which were rectangular rooms and similarly shaped palace ball rooms.

The reverberation time is still more or less the same as that in the mediaeval age.

C 3.4 Baroque Period

See generally (Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.).

The Baroque lasted from about the year 1600 till 1750 and the most significant representatives of that period in music were Bach and Handel in the north of Europe and in Italy Vivaldi and Corelli. Typical music shapes of that period are the chorales that were not accompanied with instruments, after that combination of sounds with instruments that are not consonant. The characteristics of the music of the Baroque are color and contrast and Bach's recognizable counterpoint and brisk tempo. Secular music was played in 2 types of spaces: rectangular ballrooms of a palace, or in small theatres that replicated these small places. Reverberation time in such spaces was intimate, dry, low, 1.5 s as in a conventional living room. In religious music we can also find two types of spaces: existing churches from the 18th century which are reverberant and where choral pieces were performed and the new types of spaces in Lutheran churches where people listened not only on the main floor but also on gallery.

It was for this kind of church that Bach wrote his compositions. Churches from the 18th century were rather reverberant and in the new type of church, like for instance the Thomaskirche in Leipzig, was originally 1.6 s., and when it was only half occupied, the reverberation time was 2.0 s. Bach was the supreme master of counterpoint, the art of combining different melodic lines in a musical composition, and such an environment was ideal for hearing the harmonic relationship between the lines.

C 3.5 Classical Period

The Classical period lasted from 1750 until 1820, a short 70 years, or from the youth of Haydn, through Mozart until Beethoven's death. These three composers are a synonym for classical music. This is a period of significant evolution in secular music. This is the period of the sonata and of the symphonies, which were acoustically much more replete with sound than in previous period. The other characteristic is harmony, including a bigger orchestra with significant, longer movements. As Leonard Bernstein explained the Classical style in his Joy of Music LB p.10: “Counterpoint is melody, only accompanied by one or more additional melodies, running along at the same time....This music is difficult for us to listen to... Today, we are used to hearing melody on top with chords supporting it underneath like pillars, melody and harmony, a tune and its accompaniment.”

The society in that period was evolving in civility, and brought new ideas in architecture. Concert halls that had a capacity of 400 were built. The reverberation in these halls was rather dry. The Holywell Music Room in Oxford of 1748 for 300 listeners had a reverberation time 1.5 s. The first concert halls were copies of the royal halls of the period, and of the past period. Vienna's Redountensaal from Beethoven's period for an audience of 400 has a reverberation time of 1.4 s. In middle of the 19th century the popularity of orchestral music grew and bigger buildings with longer reverberation times were built. For instance, the old Boston concert hall had a rectangular plan for 2400 people and a reverberation time of 1.8 s. The Gewandhaus in Leipzig (destroyed in World War II), for 1560, had a reverberation time of 1.6 s. Beethoven’s grand symphonies, from his mature time, were written in the scope of his great imagination for the very reverberant halls that were to be built only 150 years later.

C 3.6 Romantic period

The Romantic period lasted the next 100 years, and is represented with composers in chronological order: Schubert and Mendelssohn, then Brahms, Tchaikovsky, Richard Strauss, Ravel and Debussy. The musical form of that time was of the secular type and in greater part was symphonic. The music is characterized with lots of harmony and orchestral color. A listener cannot define different melodies, as in the Baroque or in a smaller segment in the Classical period. The music glorifies harmony in its fullness, all the drama, expressiveness and emotionality. The spaces of the period supported and made possible that fullness of sound and low grade of differentiation. The characteristics of a good symphony of that time are gained with a reverberation time of 1.9 to 2.1 s with a small ratio of sound that arrives from the performing group or from the nearby side walls to the great reverberant sound energy that follows. Composers of this period sometimes wrote with a specific concert hall in mind. Wagner composed *Parsifal* for his Festspielhaus in Bayreuth, Germany, Berlioz composed his requiem for les Invalides in Paris. To describe the acoustic methods of the romantic period here are examples of two halls. The Musikvereinssaal in Vienna, for example, completed in 1870, has a reverberation time at mid-frequencies of about 2 s when the hall is fully occupied. The hall is small enough for *ff* orchestral effects to sound very loud, and its narrowness, which emphasizes the early sound reflections from the sidewalls, lends both significant definition and spaciousness to the music. The Concertgebouw of Amsterdam, which was completed in 1887, also has a reverberation time of 2.0 s at mid-frequencies, but as it is wider it emphasizes the early sound reflection less, therefore, the music played in it emerges with less clarity and more fullness of tone.

C 3.7 European opera

During different historical periods, opera design was consistent. From the year 1700 on horseshoe shaped theatres were built with ring of boxes one atop the other and a crowning gallery of low-priced seats. The form reach its apogee in the Teatro alla Scala, Milan, completed in 1778. These opera theaters appeared in the more than less identical outer and inner space design in the whole of central Europe. This was an ideal situation for composers who knew this, because their tasks being facilitated since all spaces had the same conditions, a reverberation time of 1.2 s. Such a short reverberation was good for understanding the libretto of the opera and was very good for the intelligibility of opera performances. In Europe it is the case that the opera is always translated to native language while in America and Japan it is sung in the original libretto. This means that in Europe the reverberation in opera houses is in most cases 1.2 s. In most cases opera houses plans in Europe are horseshoe shaped, while in America and Japan the reverberation is longer because intelligibility is not crucial. Quality opera houses in Europe with a typical European way of listening to opera are:

Naples San Carlo, Paris Garnier, London Royal Opera, Vienna Staatsoper, Munich Staatsoper. On the other hand, examples of buildings for typically non-European ways of listening to opera are: the

Theatro Colon in Buenos Aires (1.6 s), Metropolitan Opera in New York (1.5 s) and the New National Theater in Tokyo (1.5 s).

Figure C- 5 Staatsoper Vienna, Austria inside view and Figure C- 6 Staatsoper Vienna, Austria, plan and section

Figure C- 5 Staatsoper Vienna, Austria inside view

(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

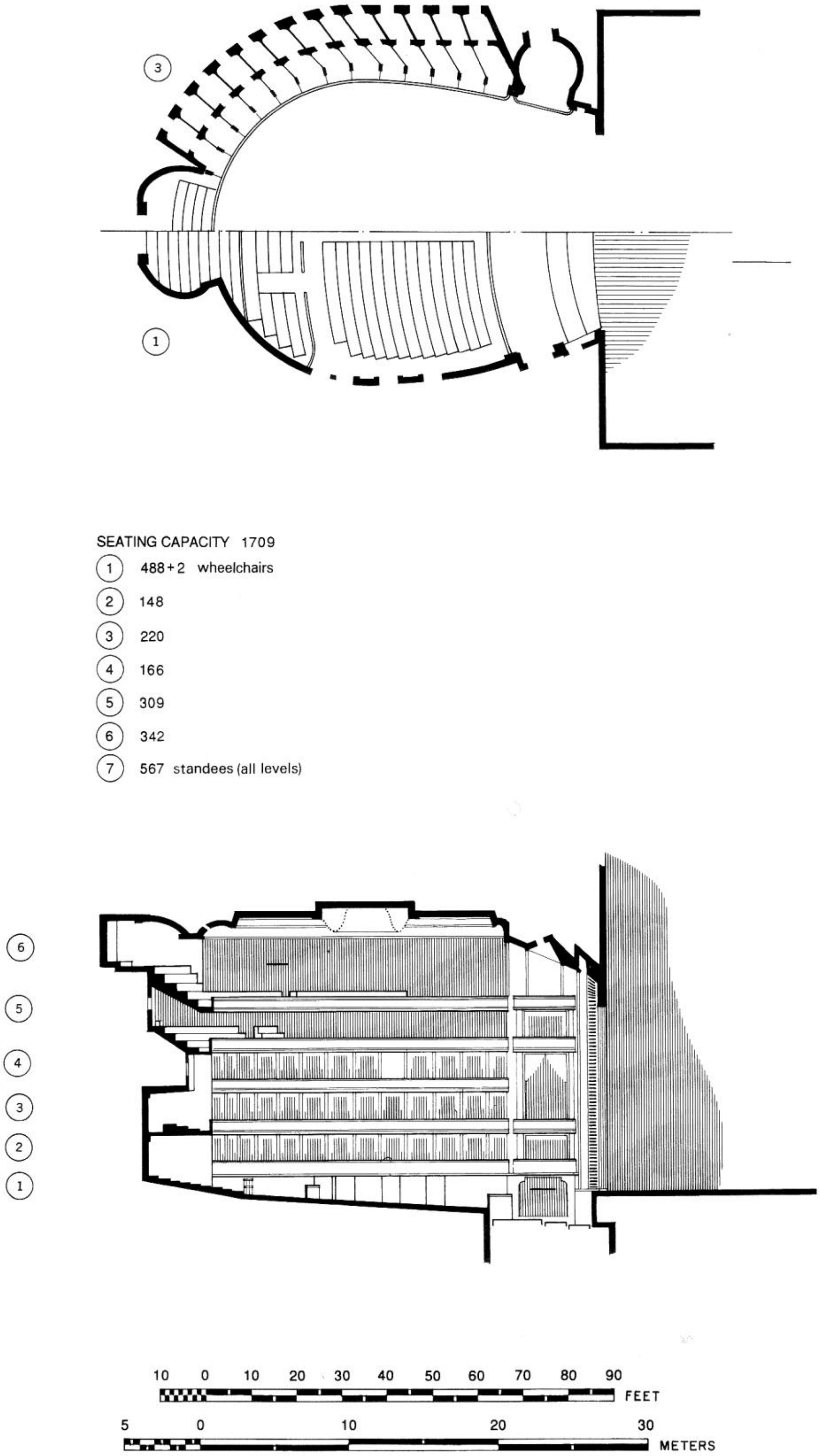


Figure C- 6 Staatsoper Vienna, Austria, plan and section

(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

It is important to explain spaces used by Richard Wagner who built for his special opera style, known as “music drama”, an opera house in Bayreuth, Germany, called the Festspielhouse. The reverberation in that space is 1.6 s and is characterized by producing a thoroughly blended orchestral tone. The orchestra is large, and numbers 100 to 130 players, in a sunken and covered pit. This way a characteristically mysterious sound is obtained.

C 3.8 Twentieth century

See generally (Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.).

The twentieth century is the period of great number of composers and because are still too close, we cannot evaluate who the leading names are. Also, the twentieth century is full of diversified styles: from neo-Baroque to neo-Romanticism with the use of new instruments, new harmonic systems such as dodecaphony and others and lots of experiments in music. The music of neo-Baroque demands dry acoustics, while neo-Romantic music demands live acoustics. The composers are in and unenviable position because they have to write music for very different places: from totally dry TV or radio studios, through the whole palette of specialized halls, then multifunctional halls to big TV studios that are designed on the principles of live acoustics.

THE CLASSICAL HALL This type of hall was built in the early 30s. It is tall, a little longer than wide and has balcony seats running on the two sidewalls and the back wall. The ceiling has a deeply coffered design and the sidewalls are lined with pillars or rounded pilasters. This hall uses a central speaker cluster elevated high over the proscenium of the raised stage. This hall is a classic example of minimalist design. It employs an elevated, central speaker position to provide fairly uniform sound levels to every seat in the auditorium. The room is a high volume hall, with ceiling 12 to 15 m high over the main floor. From the viewpoint of the speaker cluster, the main floor, two sidewalls and rear wall are nearly completely absorptive when the hall is fully occupied. Each sitting place occupies 2 m3 or 0.9 m2. The hall is of dimensions 60 x90 m. The hall has 7000 seats on the main floor. The rear balcony would be 15 m deep and provides 1250 seats. The sidewall balconies are about 9 m deep and provide 1000 seats each. The total seating of the hall is 9250 seats. The volume of the hall is 90000 m3. Empty it would have a reverberation time of about 7 s. The average absorption coefficient of the surface of the hall is already about 0.125 including atmospheric absorption effects. When occupied the reverberation time of the hall is 3.45 s. This was too reverberant because these were the early days of marble surfaced halls. They used acoustic plaster as absorption material; this is no longer used. Three sides of the hall absorbed 31% of the direct sound during the first reflection. Sound reflected reduced its strength by about 2 dB. Sound making a round trip in the hall from the proscenium into the audience and back is attenuated to 62 % of its original strength, about -2,5 dB all in one round trip time period of 1/10 second. After one second, there will be 20 such round trips and the overall sound will have dropped by about 25 dB in volume. The hall will have a reverb time of about 2.4 s. Adding a stage curtain that shows even when pulled back will lower the reverb time to about 1.8 s. This is a reasonable reverb time for a large hall.

The traditional halls were made out of heavy rock blocks or poured-in-place concrete walls with a ceiling made out of wood or concrete beams. Through changes of the style, construction ended up simplifying to reduce costs. Today, concrete blocks or tilt-up concrete walls are used to outline the space and the roofs are made out of corrugated metal supported by exposed metal trusses. The shell of today’s halls is built not very differently from an industrial space. Generally, the old halls have the interior surfaces that manage the sound. The seating, the height and the interior architecture all work in unison to produce the required intelligible acoustic condition. The reflecting surfaces of the hall provide for some early reflections but not many. The right volume size of the hall helps to avoid generating late reflections. The multifaceted ceiling and upper wall surfaces further act to diffuse late reflection. The audience provides the acoustic materials that act to control the reverberation time. Lots of architects follow the new design trend in hall design and it is very different from the classical auditorium. These new spaces are large concrete boxes that are decked out with sculpted wood, plastic, metal, lexan and sometimes even glass panels. The hall is full of big, curved panels that are suspended off the walls and again high overhead. The new look and sound in halls, churches is obtained because of their blacked out very high ceiling. So the sound tends sometimes to be too technical because of those floating reflecting panels on the ceiling. These floating acoustic clouds provide for early reflections, diffuse and weaken the late reflections and regulate the reverberation level and decay rate. The audience provides some acoustic absorption and the rest is locked way up out of sight, behind the acoustic clouds. In between these two styles we find in the recent past large auditoriums with padded sets and carpets and on the ceiling there are numerous tiles on the ceiling. This type of hall is also a large concrete box but its interior surface has been built out to create a very dead hall. Its design seems directly opposite to that of the classic concrete and marble auditorium. There is no early reflection design into the space, certainly no late reflection and as well no reverberation. The only heard sound in the hall is the direct sound from the loudspeakers. Such a hall is built on the supposition that if reverberation is bad for speech, then an acoustically dead space must be good for speech. These spaces are so big and so dead that the audience suffers from sensory deprivation. Distributed sound systems have to be installed in the acoustic ceiling in an effort to help inject life back into the space. Because they are so acoustically dead they could be used for making TV shows.

From the beginning of the twentieth century audiences grew in numbers and lots of European, American and Japanese metropolises were established as towns with a music culture. In the most recent period Japan has been established as the leader in the musical field and the capital of Tokyo has 10 symphonic orchestras, numerous conservatories and a wide audience.

Retrospectively, in consideration of sound quality in different epochs it is evident that every period has its demands. The question is then whether demands of today s image of high quality sound is just one of the images or the ultimate. The answer is that image of sound of today is also just one type of image and as our society will change in the course of time, so our image of what constitutes high quality sound will alter. Because of that the possibility of developing method for quality sound will always be limited to historical image of high quality sound, related, in other words, to the currently lived period of society.

Our time is different from historical periods in that it tolerates the varieties of previous ages and the effect of this tolerance inheres in the superimposition of various standards, as often revealed in the prefix multi. superponating everything together what is often revealed in prefix multi. As for tolerance, the current age both embraces the truths of other periods and uses technological progress. This tolerance is evident in fact that romantic music is played in different sound quality and the evidence of technological progress is seen in performance of modern types of music. The superimposition of one element on another is also the part of our time. It is evident in every element of society from furnishing to melting pots of cultures. Superimposition in the image of sound is evident in the auditory field in contemporary music works and also in the spatial field in variable acoustics.

Does the image of quality sound evolve? It is evident in past 30 years of research in the field of sound that the image or expectations of high quality sound is evolving. But, in the same time we appreciate sound images from previous periods and endeavour to perform music in such a way as to produce sound as it would have been in that particular period. But also, tolerance is typical of the contemporary period. The same questions are being asked when dealing with old chateaux in contemporary times. What is the type of preservation is to be applied? Romantic period liked old artefacts to remain old and to spread romantic atmosphere around them. Contemporary preservation has different methods in dealing with old artefacts depending on their historical values, depending on material issues, depending on how damaged they were, depending on what period it is that is to be preserved. Our modern preservation overlays numerous possibilities. That is also the case with sound images. We are tolerant to all images of sound qualities from periods before and to new sound images that are evolving with new technology. Because of that we can not easily answer the question what is high quality sound. The danger with tolerating all those sound qualities is that it may lead to the acceptance of low and not high quality sound. But in defining limits of that tolerance, the image of sound should become clearer.

SECTION C 4 Methodology - basic terms

C 4.1 A list of seven essential attributes

A list of seven essential attributes of concert hall acoustics by Leo Baranek:

1) Reverberation: RT and EDT
2) Spaciousness: BQI
3) Loudness and warmth: Gmid and G125
4) Intimacy: ITDG
5) Surface diffusivity index: SDI
6) Clarity: C80
7) Hearing on stage: ST1

This may be further reduced to:

1) those relating to clarity: intelligibility, articulation, definition,
2) those related to audible room effects or ambience (sound quality, spaciousness, enhancement and
3) those related to loudness.

Clarity is usually a physical measurement of the ratio of energy in the early phase to the reverberant sound, the ratio that is expressed in dB by C_{80}. In general, clarity decreases with increased reverberation and vice versa. An interesting thing about clarity is that conductors will express satisfaction with a rehearsal hall that has a C_{80} of +1 to+3 dB unoccupied so that details of music can be heard. But at a concert they prefer a more reverberant space, a C_{80} equals -1 ,dB to -4 dB. C_{80} is highly correlated to reverberation time so it cannot be used as additional way to estimate the acoustical quality.

A room ambience is the effect of enclosed space and, depending on details, can in the case of speech affect both clarity and naturalness and in the case of music, affect clarity, tonal quality and spaciousness. A number of objective measures deal with two parts of ambience: reverberance and spaciousness. For reverberance RT, and EDT early decay time, the time expended for the first 10 dB of reverberation decay is multiplied by 6 for a 60 dB decay time extrapolation. EDT is reciprocal quality to clarity. Good speech acoustics equate to poor music acoustics. About early time reflection, reflections arriving within the first 50 ms will usually contribute beneficially to speech clarity, those within 50 to 100 ms may or may not be beneficial and those coming later will not contribute to clarity and can be harmful, but still could be used for ambience.

For spaciousness the intramural cross-correlation coefficient IACC, a measurement of dissimilarity of sound arriving at the left and right ear and the lateral fraction LF, a ratio of lateral-to-omni- directional energy arrivals is usually integrated over the first 80 ms. Two types of spatial quality are described:

ASW, apparent source width, related to stereo effect or enlargement of the sound space, and the LEV listener envelopment, related more to surround-sound effect of room impression. Recent researches show that ASW is strongly influenced by the strength of lateral reflections in the early reflection period while most significant for LEV is late arriving lateral energy below 1000 Hz. Similarly, two types of reverberance are observed, one related to singing tone or liveliness during running music and is defined with former reverberation EDT and the other is related to the persistence of sound heard after a stopped tone and is defined with latter reverberation or RT.

Loudness is largely a function of hall size and seating capacity, and the sound power output of the source orchestra is a fixed quantity. Sometimes a designer should be concerned with avoiding excessive loudness in a small hall and how to make the loudness efficient enough in a very large hall. Loudness cannot be separated from clarity and size of the hall because clarity is influenced by the relative strengths of sound and noise. Loudness is rated by the objective measure, G, called strength factor or loudness index.

These seven criteria are of major importance when researching a methodology for the attainment of high quality sound. These criteria are contemporary major elements in methods for getting quality sound. Using these elements we are asymptotically approaching high quality sound. These elements are essential for getting quality sound and other criteria are only additional and not of such great importance. These elements will also in the future stay very significant; they can be only merged together in a new element or fulfilled with new ones.

C 4.2 Shapes of the space

C 4.2.1 Shoebox shape

SHOEBOX APPROACH Acoustic success is not guaranteed with the use of a shoebox form, particularly if insufficient diffusion is employed. In shoebox halls there is common problem of mutual misunderstandings on the stage because of the high stage ceiling.

1) Except for the shoebox shape, other aspects of design should be applied in this type of space design
2) performing area configuration,
3) proper volume,
4) echo control
5) good sight lines
6) adequate diffusion is also important.

The modern shoebox geometry seems to be applicable only for 2000 perhaps 2500 people, due to the lateral reflection. Increasing the capacity of the hall, the rear row could be too far from the stage for good visual contact. Panels should be carefully introduced into a hall. Panels can help to interrupt the focusing effects of for instance multi-barreled vaulted ceiling. These allow the clear space above the panels to add to reverberation volume, while assuring good distribution of early reflected sound. More recent studies suggest that the triangular panel shape used at Tanglewood is optimal and that the panels send evenly strong reflections to the audience. The sound quality for a full orchestra with chorus is excellent, and better than one would expect from such a large, simple structure. Sound reflecting panels can help halls' interiors to provide early reflection without sacrificing the high volume required for reverberation. With sound reflecting panels there is no more limitation for the shape of the performance halls. For this reason, fan-plan halls were built and one of the best is Tanglewood.

Meyerson Hall in Dallas, Texas, is a successful modern shoebox hall. In this hall there is an height-adjustable sound-reflecting surface suspended over the performing area and it improves the ability of musicians to hear each other on the stage. Shoebox halls without such reflectors often have less than ideal conditions on stage because of the high stage ceilings.

The shoebox approach to concert hall design is analogous to musical instrument design. There is a considerable amount of information about violin acoustics, but most successful new violins have designs based on old violins. Similarly, new concert halls often copy successful old ones. Old halls are not smooth and slicker, neither are new halls.

A large number of excellent halls are shoebox–shaped. Halls of different shapes could have the same measured numbers but might not sound exactly the same. So, there stands a thesis that non–acoustical factors contribute to the acoustical quality judgment of listener and such qualities are the beauty of the architecture and the quality of the performances.

C 4.2.2 Other shapes

There are two other significant shapes to be considered other than shoebox shape. These shapes are: vineyard shape and fan shaped halls. Horseshoe shape is considered as the best shape for opera houses.

Next step in evolution of the shape is designing nearly circular halls and one of the first important halls of this type was the Philharmonie in Berlin. This type of shape is called the vineyard shape. In this hall panels are used to complement irregularly shaped wall and ceiling surfaces to distribute the sound energy.

The experience of several acoustic consultants indicated that concert halls in-the-round are not the best choice for a basic design, unless sophisticated use of electronics supplements the natural acoustics of the hall or unless a relatively small portion of the seating is behind the orchestra. Musical instruments and the human voice are directional, and for those seated behind the orchestra, lots of expected sound is lost. In fan shaped halls a flat floored auditorium should be avoided because of the poor sightlines. And even the most single-purpose concert hall will generally be used for lectures, popular music concerts, film viewing and conventions.

Below is a comparison of shoebox shaped hall, which is the best shape, with fan and vineyard shaped halls. The shoebox is the best shape because parallel sidewalls assure the audience the lateral reflections essential to achieve the desired acoustical attribute spaciousness. Fan shaped halls have not been as successful acoustically. They can achieve good reverberation, but cannot achieve the same strength of tone. In the first half of the hall the strength is the same as in the shoe box shaped hall but in the second half of the hall the level of sound is attenuated because of the sidewall, which are opened up. The best of the halls in the category of fan shaped is the Tanglewood Music Shed, designed by Lenox, Massachusetts. The hall has a short ITDG owing to the suspended panels, triangular in shape, of different sizes, which consist of 50% open area, that hang over the stage and the front part of the audience. They are of the major importance for acoustics in the hall because they reflect about half of the early sound energy down onto the audience, arriving shortly after the direct sound, in that way giving the music quality heard in classical rectangular halls. The panels are transparent to low-frequency sounds, so the early bass reflection arrives from the ceiling. Those reflections are delayed in comparison with the violin that reflects from the panes, by only 10 m of travel distance. The time difference introduced by 10 m of travel is about the same as that between the bass and the violin player on the stage. Lateral reflection does exist and is generated by panels, but not to the extent found in the smaller rectangular halls, so BQI is measured as 0.35. The sloping panels around the upper periphery reflect sound onto the audience in the back half of the hall, augmenting both the direct and reverberant sound. The hall is successful in providing equal sound value wherever one sits. This panels that consists of canopy and enclosure that are arranged around the orchestra are the result of a six-year study. So, the low ceiling over the stage and front part of the audience (almost 50 percent opened) produces the necessary short ITDG reflections in the hall, yet leaving the upper volume of the hall available for reverberation. On the stage, the enclosure/ canopy also contribute to excellent ensemble playing. The most successful non-rectangular hall, seating 2325 is the Berlin Philharmonie. The orchestra is seated near the center of the hall and the audience is situated on 14 trays, each on the different level .The acoustical consultants believed it to be important that early reflections should come from overhead, so the ceiling is tent-shaped. An array of panels hangs high above the stage. The acoustics varies from one tray to another. The best seats are located in the front quadrant of the orchestra. The architectural effect is breathtaking on first entrance to the hall.In the C 6.2 Generally about acoustic planning of Part C there is more detailed description about shapes of a hall.

Figure C- 7 Philharmonie Berlin, Germany, inside view and Figure C- 8 Philharmonie Berlin, Germany, plan and section

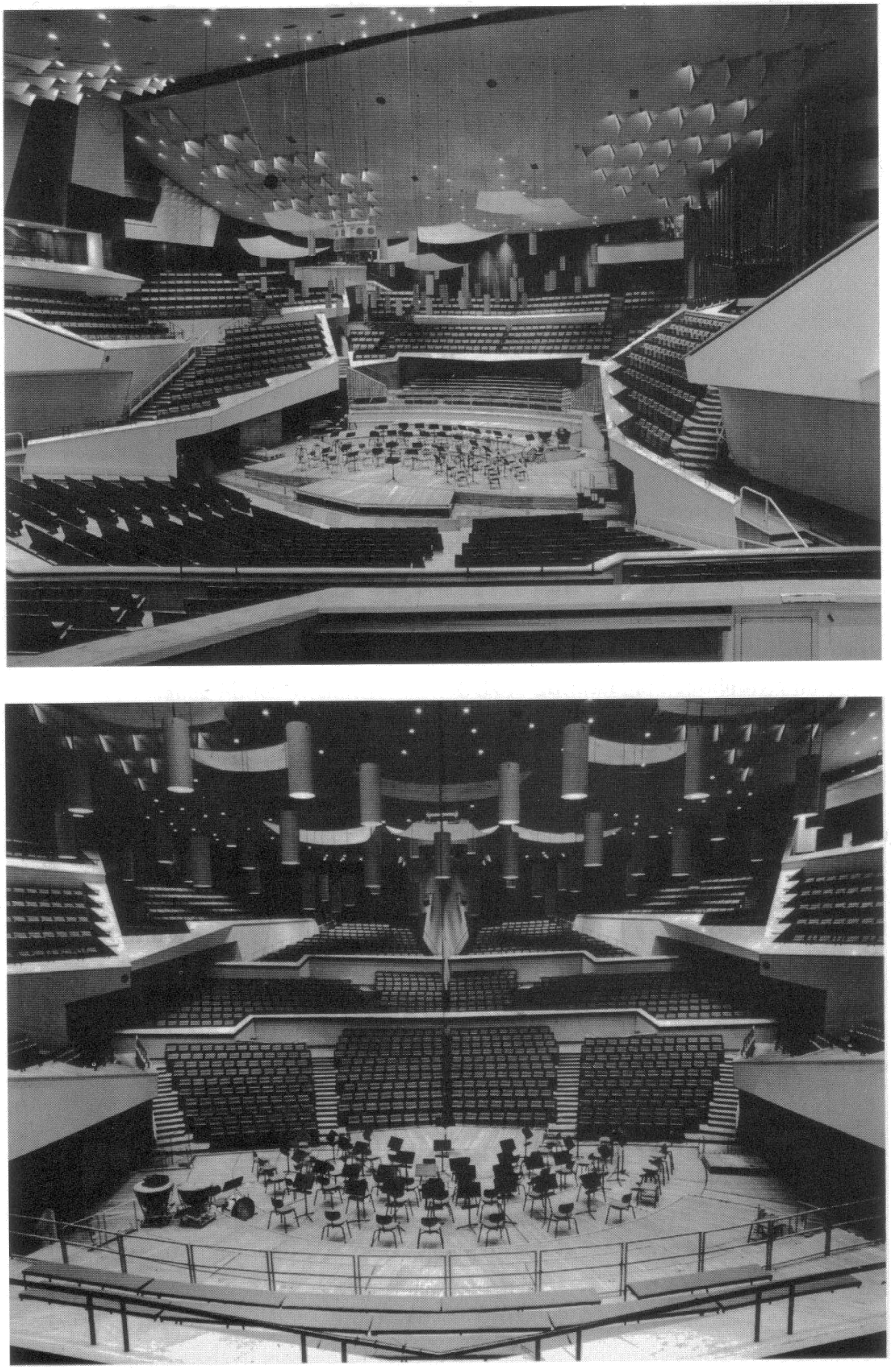


Figure C- 7 Philharmonie Berlin, Germany, inside view

(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

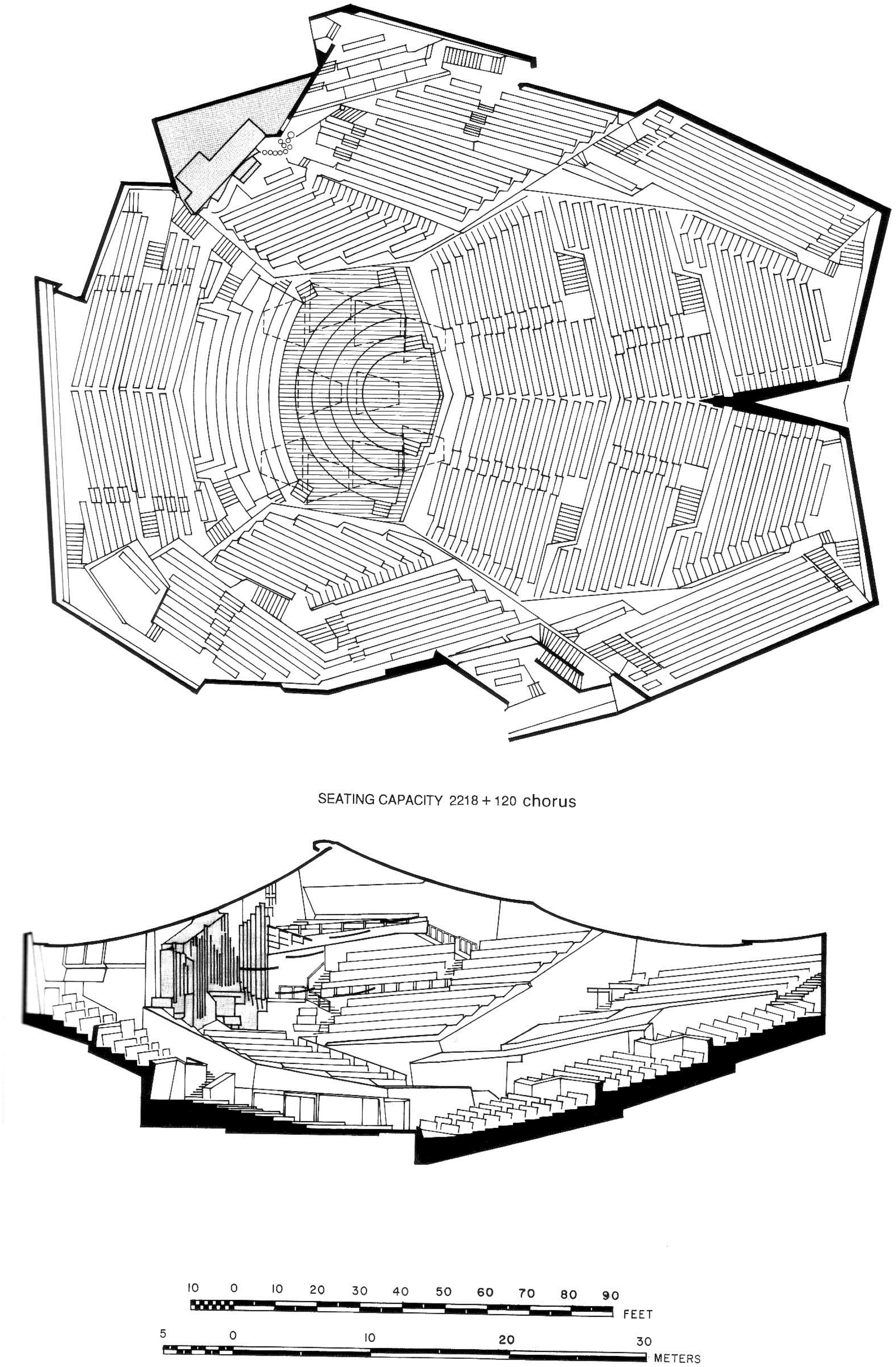


Figure C- 8 Philharmonie Berlin, Germany, plan and section

(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

The shape of space is the question of creativity and professional competence. In contemporary research for the methodology for arriving at excellent sound the shape is often examined. It is very important to be familiar with the characteristics of shapes, which are a shape's advantages and disadvantages. But it will always come to the point in the project where the architect has to pick a shape and declare that the design will subsequently be matched to that shape. The decision about the shape of space does not lie only in sound qualities but in the numerous decisions the architect has to make and to balance between. Therefore the question about the perfect shape is very important but is never going to be the ultimate input because of the other functions the hall should have, apart from providing good sound qualities. Knowing that it is important to develop and to know lots of shape types.

SECTION C 5 Which characteristics of sound should be avoid

The responsibility of the architect in planning a sound-demanding building is great, because the space should be carefully selected and interrogated before the architectural design is fixed. A hall that is shaped so as to create echoes and that has a minimum of early lateral reflection and accomplished with over-absorption is almost impossible to repair after opening.

C 5.1 Echo

Types of disturbing sounds that are unwanted in the space are: long delays, discrete reflections, echoes, focused reflections, repetitive reflections (known as flutter echoes), standing waves or other undesirable changes of the original source.

Echo is a disturbing part of the sound, but also too long a reverberation can be perceived in a space as a noise.

Echo is a reflection that is strong, rather late, with a known origin. If one hears many reflections at one time from seemingly no special direction, this is known as reverberation. Generally, any echo is bad and loud reverberation is also bad. Echoes usually bounce off the back wall of the auditorium and because the person on the stage is farthest from the back wall, the echo heard by the performer is the most delayed.

Loud reverberation upsets the timing by blurring everything together. It is especially detrimental to speech and music in small hard-surfaced rooms and the effect is like the effect of singing in the shower. Quiet reverberation contributes to the feeling that a larger than life experience is taking place because it adds spaciousness to the effect. It also adds dramatic flair to the speech. It is essential to acoustic music sources such as an orchestra, ensemble, choir or organ. But, reverberation tends to ruin the presentation of modern electronic bands because they are amplified by high volume loudspeakers and the listener is supposed to hear the sound of performers breathing, which in case of an opera is not wanted. Such quiet sounds as singers’ narration or breathing in modern electronic bands are a part of the performance and are supposed to be loud. That is why TV studios will be deadly in the sense of reverberation. For in TV studios most of the sound is made by modern electronic bands. And yet there is also a totally opposite approach to equipping TV studios to get the reverberation time of 2.5 s, which is quite long. This approach with long reverberance is in accord with the philosophy of using reflected sound from the direction of the performer. The former approach of using non reverberant studios is in accord with the philosophy of using direct sound from a performer. The concept with long reverberation is an interesting conception because if the noise is a little too loud then turning up the volume of the loudspeaker would not have the same effect if there were no noise and the loudness of the sound were less. This is because a loud sound is uncomfortable. This also depends on the content factor. People expect to hear a conversational style lecture at a conversational sound level, of 60 dB, a quiet voice at a quiet voice level of 40dB and a raised voice at a raised voice level of about 70 dB.

Standing wave is another kind of unwanted sound effect. Standing waves distort the bass and lower midrange frequencies from 300 Hz on down. It is formed only in low frequencies and often in spaces that have a rather low ceiling and with dimensions of space the where proportions repeat themselves. For instance, where the ceiling is twice as high as the width of the space. These exact proportions can contribute to standing wave, and the sound bounces between the parallel walls like a ping pong ball.

There are some room dimensions that produce the largest amount of standing waves.

1) Cube
2) Room with two out of the three dimensions equal
3) Rooms with dimensions that are multiples of each other

Figure C- 9 Favourable room dimensions

	Height	Width	Length
A	1.00	1.14	1.39
B	1.00	1.28	1.54
C	1.00	1.60	2.33

Figure C- 9 Favourable room dimensions
(Bellingham;Web Page;*Room Acoustics*; 2003-2006.)

Parallel walls should be avoided because of the possibility of the standing wave effect. These are specific types of standing waves that are called room resonance modes. The bass sounds are stronger near the walls and especially in the corners, where standing waves tend to collect. Chairs or sofas can be moved away from the walls or corners to reduce the standing wave.

Parallel walls also can produce flutter echo, which is repetitive reflection, and we hear it as ringing, while a standing wave booms. A flutter echo is formed at a frequency higher than 500 Hz. Flutter echo, in fact any kind of echo can be reduced in two ways, by absorption material or with sound diffusion.

C 5.2 About noise control in a hall

See generally (Noxon;Web Page;*Auditorium Acoustics 101,102,103,104*; 2002).

Competing with the audience reception of the direct sound is noise. This background noise masks out an important part of the direct signal. Developing the voicing of the auditorium starts with how much acoustic material needs to be added to the hall in order to produce the correct reverb time for good listening. Reflectors are added to enhance the presence of early reflections. Some late reflections are absorbed, others are split with diffusion, and others are kept intact but pushed forwards in time into the early reflection period or backwards in time into the reverb period.

Reductions in room to room sound levels of 20 to 50 dB or more are generally needed effectively to isolate typical building activities from one another.

The acoustician, the person brought in to voice the space, is much more concerned about the listeners not hearing sounds that have passed by them. In most cases acoustic specialists in hall design are the only persons that are involved in setting up the surround system of the hall. At this time, the hall is mostly finished and it is then impossible to change conditions to achieve better conditions for the emission of sound. Amplification systems in this case can be rather expensive.

A gym usually has a poor signal to noise ratio (SNR). A good signal to noise ratio is important when trying to develop a hall instead of a gym but acoustics is not about absorbing all the noise that is not direct sound, and direct sound is only 1/10th of 1% of the sound energy.

Absorbing all the noise is not wanted for acoustics. That way you get a dead hall, which is the same as getting a gym instead of an excellent concert hall. In auditorium acoustics, it is all about reflection, not loudspeakers. In order really to understand speech, the noise level of sound should be about 15 dB quieter than the direct sound. That is a signal to noise ratio of 15 dB. It is just barely possible to understand speech if the noise level is 0 dB. Understanding is poor with 5 dB SNR, good with 15 dB SNR and excellent with a 20 dB SNR. When using loudspeakers, people prefer the sound of the natural speech, about 65 dB.

However, as shown in previous chapters the sound does not consist of just the direct signal and it is not enough to turn up the volume of the loudspeaker. For loudspeakers it is also important how the sound is reflected. Good sound includes lots of early reflections, which help a listener to understand the sound. In the first 60 to 80 ms the brain cannot distinguish the difference between direct sound and early reflections.

If the sound from a loudspeaker is loud enough to be heard, the only thing that can ruin intelligibility of the sound is too much noise. The louder the noise becomes, the less we understand the sound.

When dealing with multiple noise sources, each has to be reduced to at least 5 dB below the tolerable noise floor, so that while all three kinds are going on together, the accumulated level does not exceed the tolerance limit, taking into account the additive characteristic of the noise in the mathematical sense. Three kind of noise are: fairly steady environmental noise: outside noise, installation noise, breathing of people; then intermittent noise, coughing, the rustling of feet, and clothes, babies crying; the third type is transitory, and includes echoes and reverberation. Noise can be acoustically amplified as much as +10 dB and then it seems twice as loud. Late reflections can be moved into the early reflection period by repositioning the reflective surfaces and can by the same means be shifted backward into the reverberant time.

If the noise source is outdoors and its dimensions are small compared with the distance to the monitoring position (ideally a point source), then as the sound energy is radiated it will spread over an area which is proportional to the square of the distance. This is an 'inverse square law' where the sound level will decline by 6dB for each doubling of distance. Line noise sources such as a long line of moving traffic will radiate noise in a cylindrical pattern, so that the area covered by the sound energy spread is directly proportional to the distance and the sound will decline by 3dB per doubling of distance. Close to a source (the near field) the change in SPL will not follow the above laws because the spread of energy is less, and smaller changes of sound level with distance should be expected.

In addition it is always necessary to take into account attenuation due to the absorption of sound by the air, which may be substantial at higher frequencies. For ultrasound, air absorption may well be the dominant factor in the reduction.

SECTION C 6 Standard method of designing sound-demanding spaces

C 6.1 Introduction to acoustical design methodology

See generally (Bonner;Web Page;*Music Building Acoustics*), (Interdisciplinary Science Reviews; Web Page;*Engeeniring art: the science of concert hall acoustics*).

An architect, professionally charged with the designing of spaces, has to think of a place that would in the best way suit musicians to diffuse their musical thought; or in some other line of activity, a place that would help other kinds of art to be expressed, and different voices to be heard. An architect in that sense ought to use knowledge about room acoustics and designing the space.

Methods of designing spaces have changed through the different historical periods: from open Greek amphitheatres, through churches to contemporary halls. One of significant step in contemporary evolution of methodic in halls is the Berlin Philharmonie where the orchestra is in the middle of the hall and the audience is placed on breathtaking vineyards levels all around it. Another example of significant evolution of methodology is the variable acoustics of Jean Nouvel in Lucerne.

Whether a hall is to be retained or abandoned and the ensemble moved to a different place depends very much upon the primary concern, the acoustics. It is also for acoustical reasons that the renovation of a hall might be undertaken. This is again the proof that acoustics is the most important segment in building new spaces or reconstructing old ones. The legendary conductor Wilhelm Furtwangler said: “The hall with the best acoustics is the hall with the best performances”. The question is also asked as to whether specific halls gain in acoustical values thanks to their age and because they incarnated the splendor of the past.

The investor and the architect should not make originality in the architectural design the highest priority. A round violin can never be made to sound like a Stradivarius.

There are two ways to make sound louder: With amplification by loudspeakers, or by adding as many reflections as possible. Many reflections will in fact form images of the sound source that are superadded to the direct sound level.

Unwanted late reflections can sound like an echo. They can be eliminated by having all late reflections absorbed, or they can be diffused by being broken into a plethora of fairly quiet reflections that do not obscure the perception of the sound.

Early sound reflections from sidewalls lend both significant definition and spaciousness to the music.

For instance the Berlin Hall is an example where the reverberation time is not unified for all the seats while on the other hand in the widely known fan shaped hall in Massachusetts the reverberation time is unified. The Berlin Philharmonie is, despite its un-unified acoustics, one of the most quoted and beloved by musicians. This is true even if the ideal is to obtain the same reverberant time and other acoustical characteristics in all seats, in all parts of the space. The best way is to get a diffuse sound field that is unified to the best possible degree at ever seat in the hall.

A diffuse sound field is achieved when the hall height is designed as least one third of the hall width and the depth of the hall. This receives support from the golden section.

C 6.2 Generally about acoustic planning

See generally (Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.).

The first scientific method ever used in acoustics was the Sabine formula that originates from year 1893 and 1898. This is the beginning of all acoustical questions. For designing an acoustically high quality hall using the Sabine formula other knowledge of methodologies for gaining quality acoustics also has to be used. The basic and general rules in designing an acoustically demanding hall are:

1) Reverberation time: dry halls are under 1.5 s. Live halls are between1.8 to 2.1 s. Reverberation times in halls with audiences are hard to measure. Most halls do not permit recordings during concerts. When possible, the measurements are made in the intervals. Measurements of unoccupied and occupied auditoriums are different and those for occupied are rather difficult. There are special procedures to simulate an audience being in the hall, and one of the newest is using absorptive foils like MOLTON that simulate absorption by an audience. This is only relevant if RT is being measured; but for calculation of EDT Baranek has measured and classified the absorption into groups: low, middle and heavily upholstered auditorium and these values can be found in the table. In other words, we can measure unoccupied space and for the same occupied space, calculate the result. Understandably, the measurement gained from measuring the RT of a fully occupied space is totally accurate. The first condition is to choose which reverberation time is suitable for the largeness of the hall and for its function.

2) Deciding for the shape and size. More detailed introspection about shape and size is in one of the former chapters.

3) Music power. Music power is created of three parts of sound: direct sound, the sound from the early lateral reflections, and reverberant sound. It is important in design that the early lateral reflections be preserved, but not emphasized to the point that there is insufficient power in the reverberant sound, so that the reverberant sound has no punch. For after some time direct sound is reflected and first we hear the early lateral reflection which is in fact the first reflection from side walls and ceiling and that reflection contributes to sound loudness within first 80 ms of time being made. Other reflected sound will be used in creating reverberation time.

4) Materials and irregularities of its walls and ceiling. Heavy walls, balcony faces. Except around the stage, the three famous halls in the top category are constructed of plaster on wire or wood lath for the ceiling, and stucco plaster on brick or on concrete block for the walls. In most modern halls where the bass response is good

> the floors are concrete, covered with either wooden parquet or some synthetic material that is cemented onto the concrete, and the walls and ceiling are constructed with materials that have a large weight per square meter. In the Boston hall, the floors are wooden because the seats are mounted on a removable floor that converts a raked floor for regular concerts to a flat, hard, floor for pop concerts. When the audience sits over the raised floor, their weight suppresses some of the vibration and the loss of bass is not excessive. The thin wood paneling of 2.5 cm strongly absorbs bass energy. For a hall that is lined with wood, the cladding should be nearly 5 cm thick if possible. For the sidewalls of many halls, wood veneer (wallpaper) on solid plaster backing is employed to give the hall warmth and the traditional appearance. An example of the proper usage of wood is the Sibelius Hall, Finland, where a large percentage of the interior surfaces are built from 6.9 cm thick laminated wood. Wood 1.9 cm thick is used for the sides and ceiling of the stage enclosure in a number of halls, because musicians believe that "wood is good" and feel more comfortable when surrounded by it. This is permissible, because the surface area around a stage is small compared to other surfaces in the hall.The stage floor is different. It is usually constructed of flexible wood over a large airspace, which will augment the sound of the double basses and cellos that stand on pins. To preserve the bass, all surfaces, except the stage floor, should be of heavy dense material. Sound absorbing materials and carpets must be used sparingly.

Before the detailed design of a concert hall is undertaken the investor and acoustician should make some preliminary decisions. Three factors are immediately involved: number of seats, reverberation time, and the approximate cubic volume.

C 6.3 Concrete calculation procedure

See generally (Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.).

Because three factors are immediately involved - number of seats, reverberation time and approximate cubic volume - we can start in two ways.

Here is the short illustration about calculation. Below, this calculation will be presented in a more detailed manner.

The first way, called A in the figures, is to determine the area in square meters of the hall if we know the G_{mid} desired, and then determine the number of seats in phase 1, in Figure C- 13. After that we will choose the volume when reverberation is chosen in phase 2 shown on Figure C- 10 and volume is calculated in phase 3 illustrated on Figure C- 12.

The second way, called B in the figures, is to begin with the number of seats desired. Way B phase 1 is shown in Figure C- 10. After that, phase 2 follows which is shown in Figure C- 11. The final phase is Figure C- 12.

Figure C- 10 For way B, phase1 and for way A, phase 2 :Optimum range of reverberation

Figure C- 11 Used only for way B, phase 2: Volume and Optimal Reverberation time depends on type of performance

Figure C- 12 For way B, phase 3: Determination of audience area with obtained volume; way A, phase 3: Determination of approximate volume according to sitting area that was calculated with the figure above

Figure C- 13 Used only for way A, phase 1. Determination of square meters if we know Gmid value. The equation for calculating number of seats should be pointed out. The equation is: Number of seats= (Square meters - 180)/0.645

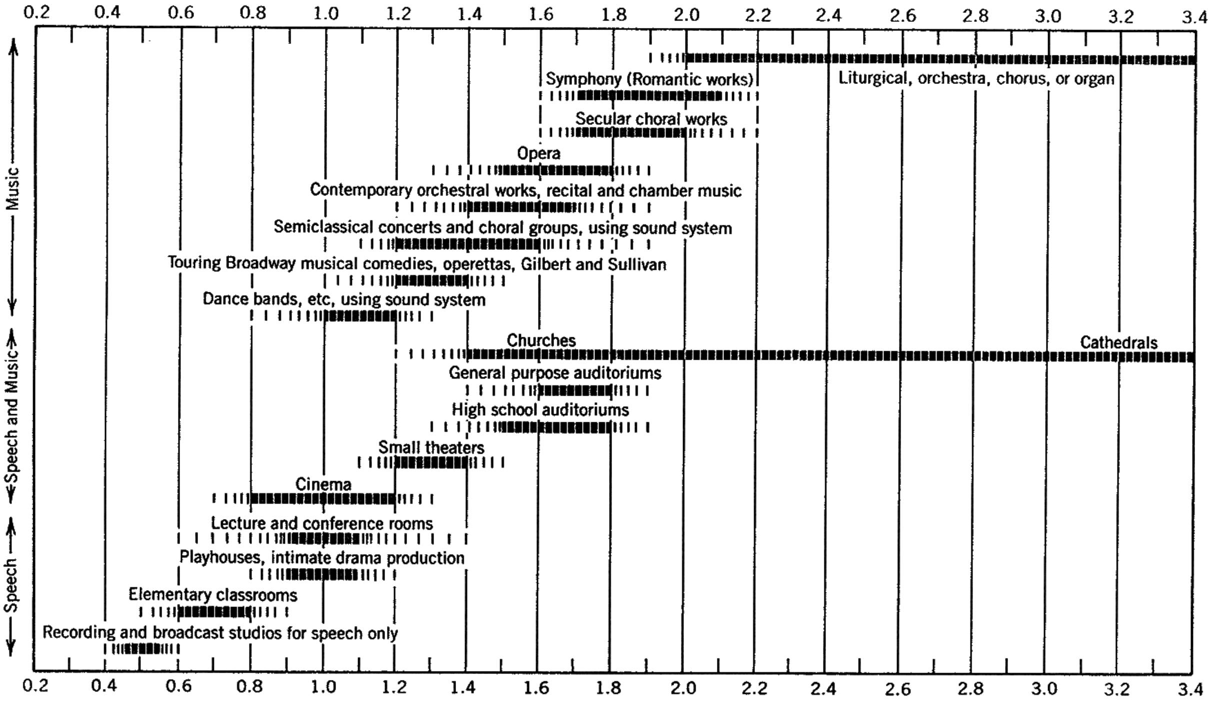


Figure C- 10 For way B, phase1 and for way A, phase 2 :Optimum range of reverberation
(Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999)

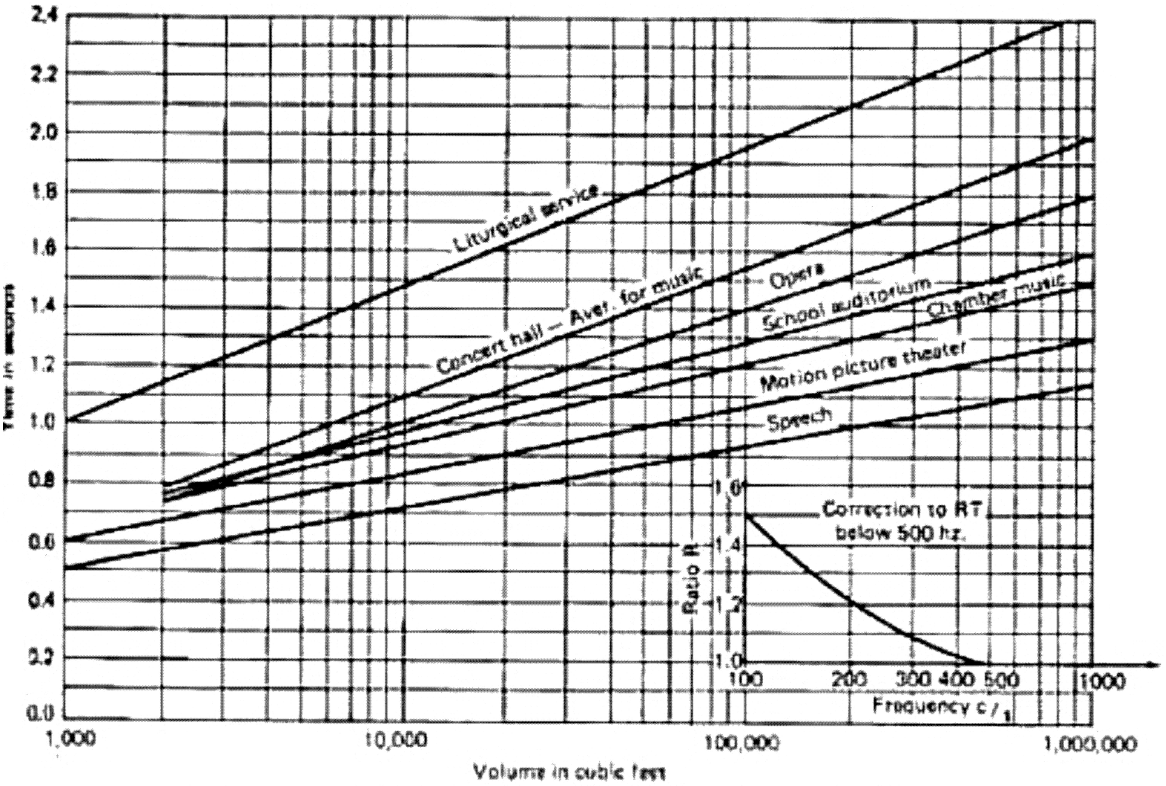


Figure C- 11 Used only for way B, phase 2: Volume and Optimal Reverberation time depends on type of performance

(A Acoustics; Web Page;*Room Acoustics*)

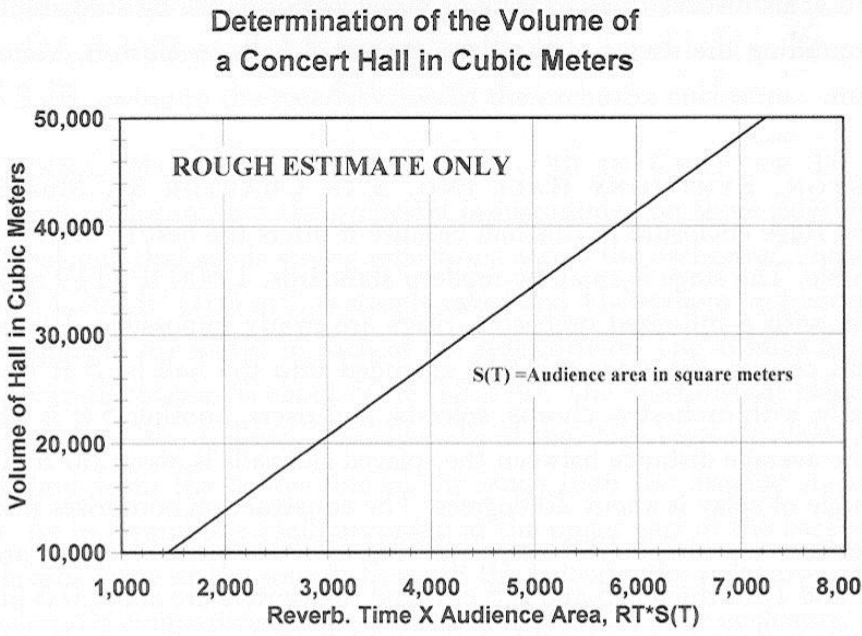


Figure C- 12 For way B, phase 3: Determination of audience area with obtained volume; way A, phase 3: Determination of approximate volume according to sitting area that was calculated with the figure above

(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

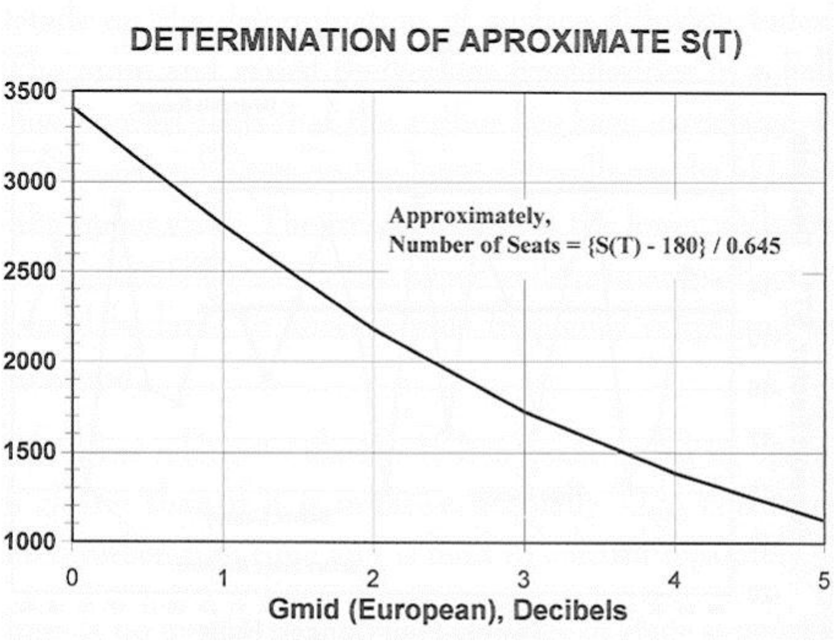


Figure C- 13 Used only for way A, phase 1. Determination of square meters if we know G_{mid} value. The equation for calculating number of seats should be pointed out. The equation is: Number of seats= (Square meters - 180)/0.645

(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

In the following paragraphs a more detailed calculation procedure is explained.

One way is to begin with the number of seats desired. The other is to begin with the strength of sound that is desired in the hall. G mid for the best halls lies between 2 and 5 dB. One starts with estimation of G mid and then ST, meaning square meters, can be obtained and out of that the number of seats with the formula: ST= (Nx0.645) +180 m^2

STxRTOCCUPIED=number on the chart. From the chart we can see that this requires Volume of about xxxxx m3.

With this estimation of three numbers –number of seats, reverberation time and volume, the detailed planning of the hall can begin.

The correct reverberation time can only be calculated after the cubic volume and the acoustical characteristics of the walls, ceiling and chairs are known – that is, the absorption of these materials. Reverberation time is then calculated with the Sabine formula: $RT=55,3\ V/Ac_0=0,163\ V/A$ (s). Absorption (A) should be adjusted to the wanted value. This means adjusting reverberation time by using different surfaces with different absorption grades.

A=αxS (m2) is calculated as a product of alpha (α) which stands in the table and is a real measure when producing one material, as in the example and the surface of the material. A =A1+A2+A3+..... where A1 is absorption in m2 for the specific material with its real surface in the hall. For greater precision the audience should be calculated, for real absorption that is 1.1 to 1.4 times greater than the actual number of listeners. Sa and SA. The first signifies the area that is occupied by the audience and the other signifies the real area of absorption and is always greater than the first one. The ratio of

SA and Sa ranges from 1.1 to 1.4. When the area over which the musicians sit is added, the total acoustical area is called ST.

Proving that outer noise, vibration or distortion will not interfere.

Minimize the effect of the noise coming from ventilation and other infrastructure in the building

Ensure that the right humidity of the air in the hall will be obtained to diminish the effect of dissipation of the brilliance in the air.

Avoid disturbing sound coming from the audience like coming from seats or passages.

Ways of calculating reverberation time:

ÖNORM B 8115 Table 3.1 for frequencies 500 Hz one finds RT or the RT should be calculated as in the following equations.

For spaces with speech function the optimum reverberation time is calculated with Knudson's formula: T_{opt}=0,32+0,17lg x V (s),

and for concert halls less than 1000m3: T_{opt}= 0,75 + 0,057 3 $\sqrt{V}$, This is Watson’s formula.

and for volumes bigger than 1000 m3 T_{opt}=0,9+0,37 3 $\sqrt{V}$. This is Watson’s formula.

Reverberation time is for places with small absorption coefficient what is explained in former Part in one of chapters, in fact calculated with the Sabine formula RT=55, 3 $\frac{V}{Axc_0} = 0.161\frac{V}{A}$ (s).

In calculation procedure one should be aware of:

1) Room acoustics. An acoustic professional keeps in mind these basic geometric rules when laying down the plan for a larger auditorium dealing with acoustical problems such as sound power, room impulse and echo problems:
2) Guaranty of good sightline between performer and listener
3) Establishing desirable early lateral reflection
4) Avoiding, in other words diminishing undesirable late reflections

The result of these basic rules could be objectively measured when disposing the plan view by measuring the dB level at sitting positions, room impulse response in the space and after that clarity, intelligibility. In this measurement, computer simulations and models are of major help because they can persuade designers and construction engineers to make correct decisions. These modern simulations demand larger investments, which have mostly not been incorporated into the budget.

Musicians, because of the nature of their job, which involves lots of rehearsals with the orchestra, are used to working in different spaces with different acoustical characteristics and are therefore more familiar with the surrounding space than most listeners, speakers and even soloists are and they can determine whether the space is supporting or not supporting. The goal of the designer is of course to materialize a space that is supportive to musicians. Sound directors and sound engineers also understand the problematic of acoustics very well. Actors are not such experts at space acoustics because they use the full range of acoustics very rarely.

Because of very narrow circle of experts in the field of acoustics, sound characteristics are often left to be decided from a subjective impression of an auditorium. In that subjective and subtle collaging of sound impressions a major role is also played by the visual impression of the hall. So, that one can not determine whether the sound impression is based only on the acoustics characteristics the audience had heard or on imaginary acoustic characteristics. Further problem of sound impression is that it depends also on , whether the performer managed to comunicate with the audience, or simply on the success of the performance.

When a quality reverberation time at lower frequencies is obtained, and this is not dependent on whether the auditorium is occupied or not occupied, other characteristics of the sound are to be sought. Those further criteria are: the warmth, sonority, resonances that are chosen should be in relation to the enlargement of the reverberation at deeper frequencies. It is clear that in performing, bass instruments should stand in front, but not in literal way, of their higher frequency fellows.

Newest researches in the field of sound source show whether the voice or instrument should be put farthest possible back, be driven to the back of the stage. This in fact does not disturb deeper frequencies, but helps them to sound full and expressive, pregnant.

There are lots of examples of gezähmten Raumen, mostly new built or reconstructions, that are in fact problematic but in the end successful in obtaining reflection that is both ergonomic, meaning appropriate to the purpose, and functional, meaning that the sound field is properly directed. The problem in buildings of this type is that they are of great volume of 20 m3 per seat, in which it is not possible to reduce reverberation according to the DIN 18041 standard. It is often very hard to reduce reverberation in halls that have a volume of 20 m3 per seat, and with halls that have a volume greater than that, it is almost impossible. These halls also have a problem with excessive reverberation in the high frequencies even when there is the audience and the audience absorption grade climbs with higher frequency. But there is still not enough absorption. The solution for these rooms is to install additional broadband absorption with emphasis on deep frequencies. The principle of gezähmten Raumen should not be used when playing deep tones in front of a reflective wall .That principle of playing deep tones in front of reflective walls is used a lot in orchestra pits and in rehearsal rooms.

With operas and concert halls with a volume of less than 10 m3 per person, even 5 m3 per person there is another problem occurring: here regularly there is a deficit of reverberation longer than 1.5 s in high frequencies and with low frequencies there is a problem of too long reverberation.

C 6.4 Design procedures and details when the concrete calculation of the room volume is finished

See generally (Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999), (Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.), (Madan Mehta;Book;*Architectural Acoustics: Principles and Design*; 1999).

In this chapter there will be more details on auditorium design and stage design. There will be a special overview in auditorium design of designing the first row, riser height, balconies and ceilings.

Designing the hall, knowing the volume of the building, and knowing number of seats.

Defining the size and the shape of the hall. Defining audience area keeping the distance between viewers and the stage as small as possible by using balconies if necessary, designing the logarithm curve so as to obtain the best direct sound.

Calculate the distance between the first row and the stage.

Designing the stage with the right proportion and the right ceiling. The best practice is to elevate it 1m higher than audience flooring. Deciding about the position of the orchestra: open pit or sunken pit or sunken open pit. Deciding about the position of the rear wall, concerning the reflection of the sound to the performers. Designing the shape of the stage to reflect the most of the sound. Designing the stage to score the best blend balance and ensemble deciding about the ceiling over the stage: fly tower for operas or reflecting ceiling for concerts or canopy or concert hall shaper.

Designing sidewalls near the stage to reflect as much as possible to the audience.

Designing the ceiling to obtain the best reflection of the sound. A ceiling pitch-tent or one with long hanging reflective panels. The ceiling should not exceed 8 m, and the maximum permissible is 13 m.

Design of the sidewalls to gain the best early lateral reflection, with such a texture as to bypass parallelism that could make echo distortions.

Designing diffusion in ceiling and sidewalls to obtain texture, brilliance, blend and sufficient glare of the sound.

C 6.4.1 Flat floor calculation

In To provide the best direct plus early reflected sound the auditorium floor should follow the calculations in the following pictures.

Staggered type of seating is shown in picture Figure C- 14 Staggered type of seating. For this kind of seating we use c value of 50 mm, which is in fact 0.05 m. If we work with normal eye-to-top-of-head distance c = 100 mm then we would get much more inconvenient distance of the first row

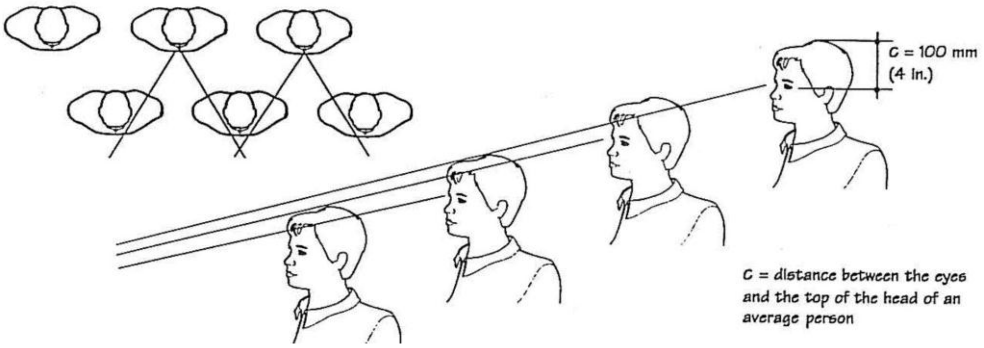
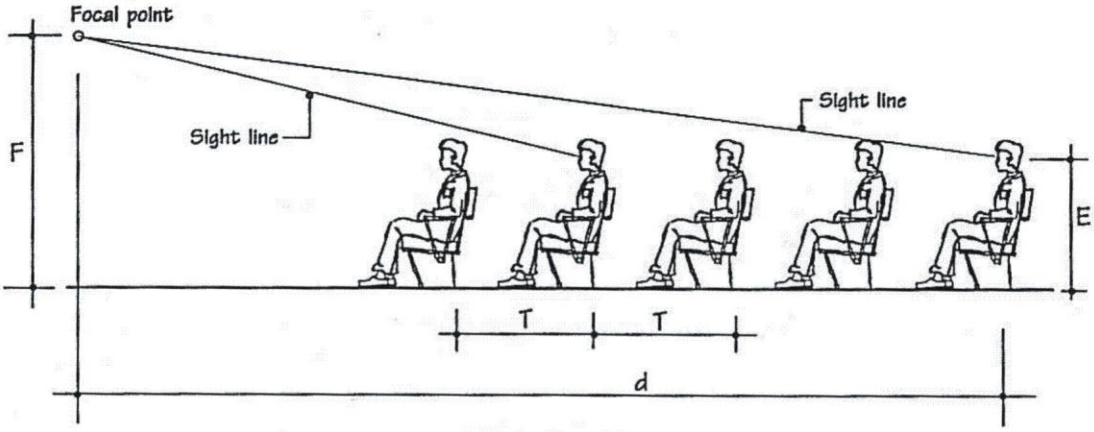


Figure C- 14 Staggered type of seating
(Madan Mehta;Book;*Architectural Acoustics: Principles and Design*; 1999)

A distance between viewers and the stage as small as possible is obtained from calculations from the picture as shown in Figure C- 15 Flat floor limitations.
The original picture contents inch figures and links to original chapters, which were removed by the author of the dissertation.



E = Height of eye above floor level, typically = 1.1m
c = 100 mm
T = Distance between rows, which varies according to the seating arrangement;

F = Height of focal point on the stage

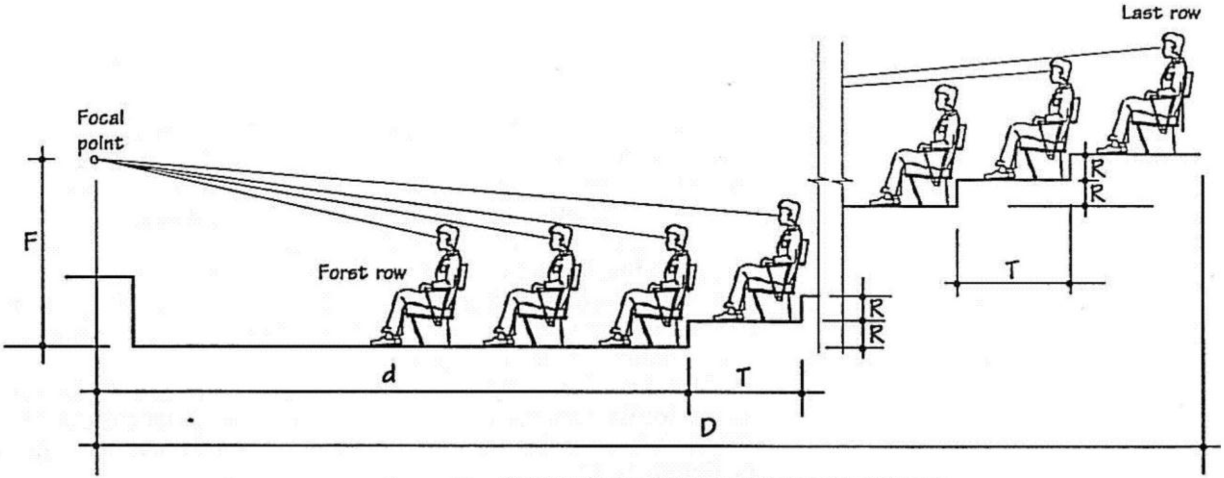
$$\boxed{d = \frac{T}{c}[F - E]}$$

Figure C- 15 Flat floor limitations.

The original picture contents inch figures and links to original chapters, which were removed by the author of the dissertation.(Madan Mehta;Book;*Architectural Acoustics: Principles and Design*; 1999)

C 6.4.2 Riser height

The riser height in the auditorium is determined as follows in Figure C- 16 Equation for calculating



$$R = \frac{c\,D - T\,(F - E)}{d}$$

c = Distance between the top of the head and the eye;
d = Depth of the flat part of the floor, i.e., the distance of the first step from the focal point
D = Distance of the last seat from the focal point
E = Height of the eye from the floor level, typically = 1.1 m
F = Height of the focal point above the floor level. Focal point is the lowest point on the stage that is required to be visible to the audience
R = Height of riser
T = Distance between seating rows, i.e., tread width

Figure C- 16 Equation for calculating riser height in an auditorium. The original picture contents inch figures and links to original chapters, which were removed by the author of the dissertation. (Madan Mehta;Book;*Architectural Acoustics: Principles and Design*; 1999)

The height of the hall must be within the limits explained in the section discussing reflection and not getting echo as a result.

It is also possible to design a logarithmically curved floor but here it has to be said that designing the auditorium floor as logarithmic curve to obtain the best direct sound had better be avoided because building regulations do not accept different riser heights in the hall.

C 6.4.3 Balconies

Balconies are used in large halls to reduce the distance between the stage and the farthest row of seats. There should be one large balcony or a number of smaller ones. The Figure C- 17 balcony design in opera houses and in a concert hallshows good balcony designs. It is not desired that people are seated beneath a deep overhang because then no reverberation could be achieved. As a general principle, the D dimension shown should not exceed the H dimension. An even better design is to restrict the opening to the height given by the angle θ= 45 degrees. With these restrictions the early decay time EDT mid is decreased by only about 10%, as measured in a number of halls. In addition, the soffit of the balcony should be shaped to reflect the early sound to the heads of the listeners.

Figure C- 17 balcony design in opera houses and in a concert hall

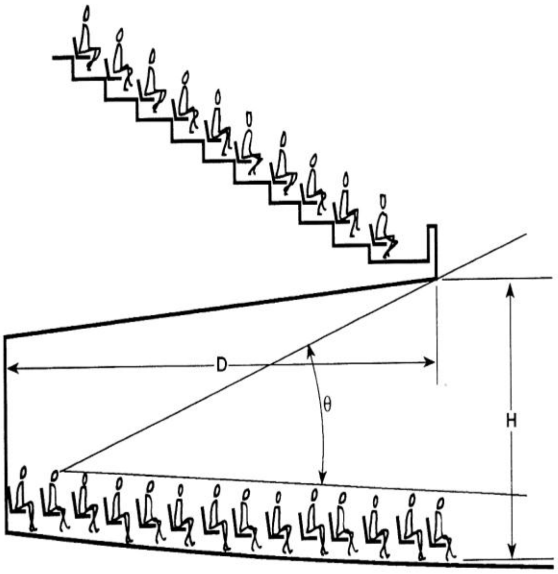
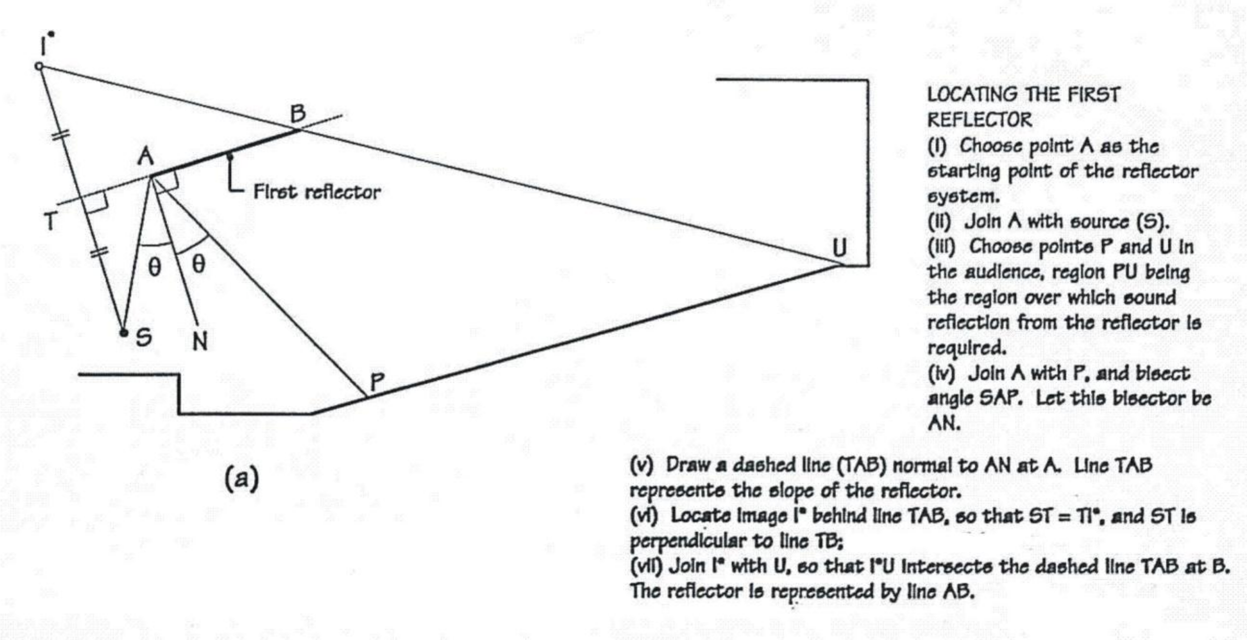


Figure C- 17 balcony design in opera houses and in a concert hall

(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

C 6.4.4 Ceiling design

Ceiling design of the auditorium is presented in the following figures: Figure C- 18 Ceiling design, step 1, Figure C- 19 Ceiling design, step 2, Figure C- 20 Ceiling design, step 3, Figure C- 21 Ceiling design, step 4. The original picture contains inch figures and links to original chapters, which were removed by the author of the dissertation.



LOCATING THE FIRST REFLECTOR

(i) Choose point A as the starting point of the reflector system.

(ii) Join A with source (S).

(iii) Choose points P and U in the audience, region PU being the region over which sound reflection from the reflector is required.

(iv) Join A with P, and bisect angle SAP. Let this bisector be AN.

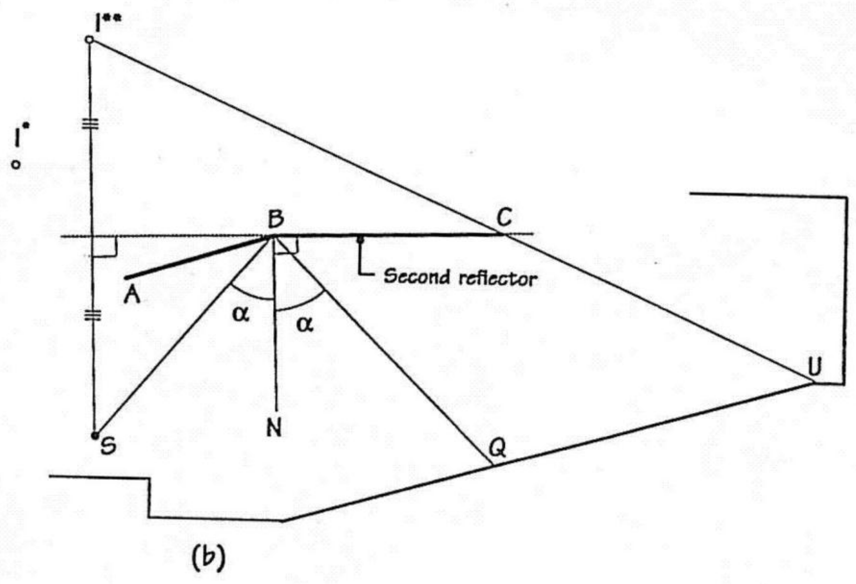
(v) Draw a dashed line (TAB) normal to AN at A. Line TAB represents the slope of the reflector.

(vi) Locate image I* behind line TAB, so that ST = TI*, and ST is perpendicular to line TB;

(vii) Join I* with U, so that I*U intersects the dashed line TAB at B. The reflector is represented by line AB.

Figure C- 18 Ceiling design, step 1

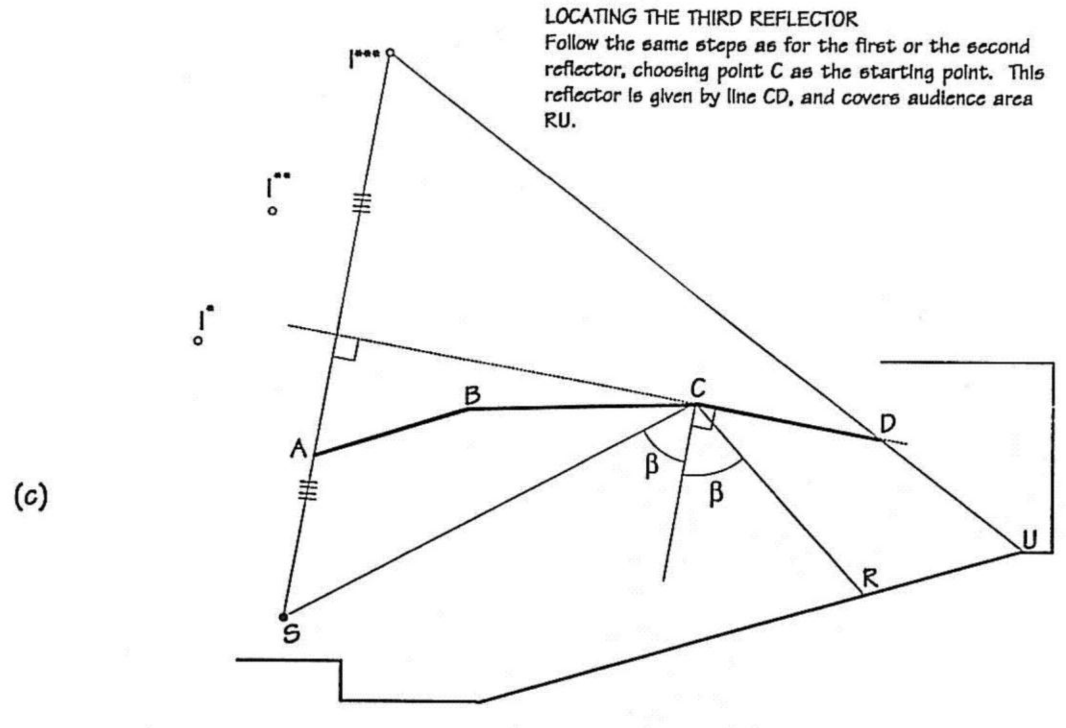
(Madan Mehta;Book;*Architectural Acoustics: Principles and Design*; 1999)



LOCATING THE SECOND REFLECTOR
(I) Point B is the starting point of the second reflector.
(II) Join B with S.
(III) Choose points Q and U in the audience, region QU being the region over which sound reflection from the second reflector is required.
Now follow steps (iv) to (vii) as for the first reflector. The second reflector is represented by BC.

Figure C- 19 Ceiling design, step 2

(Madan Mehta;Book;*Architectural Acoustics: Principles and Design*; 1999)



LOCATING THE THIRD REFLECTOR
Follow the same steps as for the first or the second reflector, choosing point C as the starting point. This reflector is given by line CD, and covers audience area RU.

Figure C- 20 Ceiling design, step 3

(Madan Mehta;Book;*Architectural Acoustics: Principles and Design*; 1999)

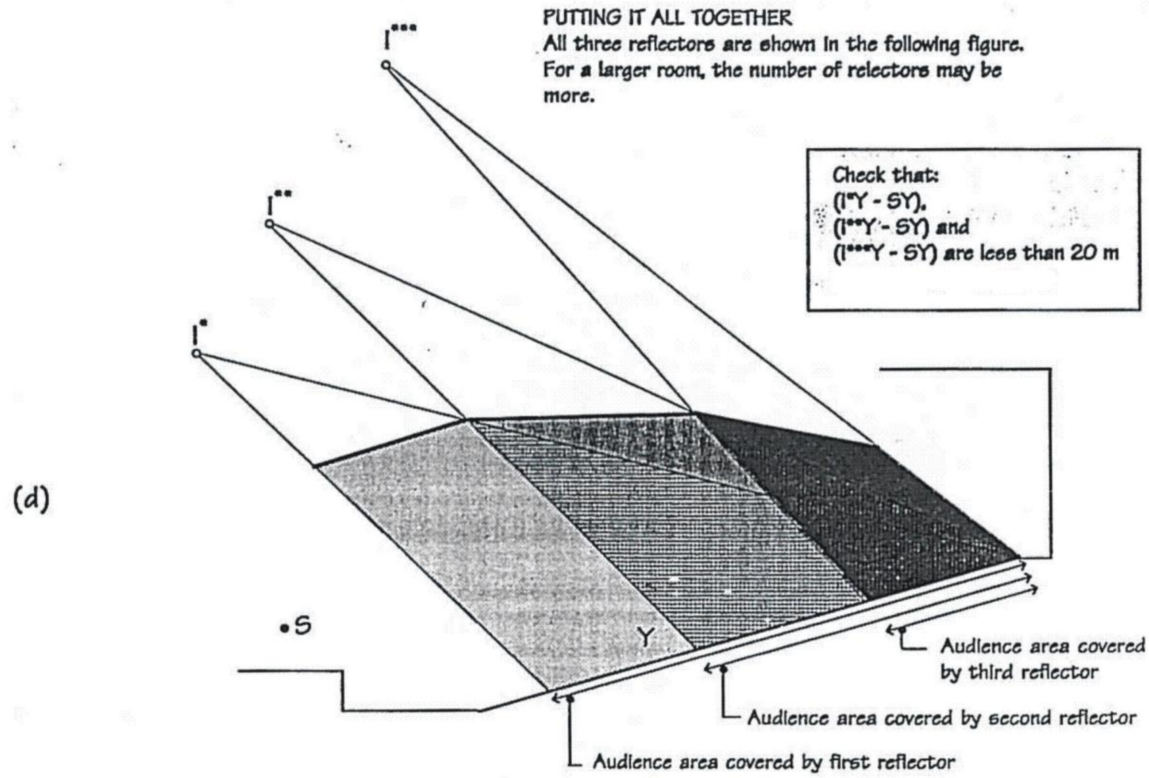


Figure C- 21 Ceiling design, step 4. The original picture contains inch figures and links to original chapters, which were removed by the author of the dissertation.
(Madan Mehta;Book;*Architectural Acoustics: Principles and Design*; 1999)

C 6.4.5 Stage

When discussing the shape of a stage, very wide or very deep stages have serious disadvantages. When a stage is too wide listeners located at one of the sides will hear the instruments located in front of them more clearly. A narrow stage makes it easier for players to hear each other. When the average width of the stage is greater than 18.3 m and the area is greater than 186 m2 special means must be provided to create early reflections to players so that they can hear each other during performance. Some combination of reflecting soffits, stage ceiling, suspended panels, canopies, shelves, and diffusing irregularities must be incorporated into the architectural design of the sending end of the hall. The difference in time can be great enough to affect the blend. When the stage is too deep, the sound from the instruments at the back will arrive detectably later at a listener. Different elements can be installed in the stage to provide emission of the sound towards the auditorium. These elements are: canopies, concert hall shapers, reflectors under the roof and above the stage, which can be shaped like the pitched tent in Berlin, while fly towers reduce reverberation time because they consume lots of sound energy that is not directed into the audience.

Calculation of maximum stage height shows that this height can be from 1 to the best chosen 1.5 or maximum 2 m high.

Balance, blend and ensemble are important parts of this stage of designing a hall. Good balance means that no instrumental group dominates another and that good correlation is established between vocalist and orchestra. A satisfactory blend means that different sections of an orchestra sound like a tightly coupled body, not like several sections striving to play together. Ensemble means that the players can play in unison without watching every movement of the conductor. These attributes are brought together by the acoustics of the sending end of the hall, which include the sound–reflecting surfaces at the sides, rear and above, and those portions of the ceiling and sidewalls near the front part of the audience. Barron (1993) states that it is desirable to provide the following areas per players for different groups of instruments:1.25 m2 for upper string and wind instruments, 2 m2 for cello and larger wind instruments, 1.8 m2 for double bass, 1.0 each for the tympani and double that for other percussion instruments. For seated choirs, 0.5 m2 per person is needed. Choir seating is in a separate elevated choir balcony, and when not required, these seats can be sold to concertgoers. For a 100-piece symphony orchestra, these requirements set a stage area of about 150 m2. If the platform has an area of 180 m2 there is a space for risers and more space for the soloist.

C 6.4.6 Additional details on designing

Chairs- comfort is important but so is the number of persons. To keep the seating area from becoming too large, the investor should not request a hall that will be occupied only a few times a year.

If the seats in a large hall are too generously spaced, the architect is likely to design a wide hall. If the architect selects the alternative of adding depth to the balconies, the balcony overhangs may shield a significant percentage of the audience from the desired reverberation. Because of that there is an optimum ratio between D, depth and H, height values, and if one wants to be more accurate angle theta that should in opera houses be greater than 25 degrees and in concert halls greater than 45 degrees. Otherwise, the back row listeners in the balcony will be very far away from the stage, thus diminishing the strength of the direct and indirect and early sound. Audience absorption is partially owing to the type of chairs, with heavily upholstered chairs absorbing more than non-upholstered chairs. The difference is particularly noticeable at bass frequencies. A common cause of bass deficiency in concert halls is overly sound-absorbent chairs. It is strongly recommended that a chair be made of molded material, such as plywood, and that the upholstering on the top of the seat bottom be no thicker than 5 cm and on the seat back no thicker than 2.5 cm and cover only two-thirds of the seat back. Also the armrest and the rear of the seat back should not be upholstered.

Upholstering of the audience chairs. When the chairs are not upholstered the audience absorbs less of the bass sound which will thus be better preserved. The Symphony Hall in Boston (1900), 445 seats, and the Leipzig Gewandhouse (renovated 1981), 369 people, covering the same floor area, ca 232 m2, are the best examples to emphasize the importance of keeping the area covered by the audience as small as possible. An audience area that is divided into a number of small seating blocks absorbs more sound than if it is compressed into a few blocks. This is because the sound is absorbed both at the sides and on the top of the audience block. So, two measurements could be distinguished: S_a and S_A. The first signifies the area that is covered by the audience and the other signifies the real area of absorption and is always greater than the first one. The ratio of S_A and S_a ranges from 1.1 to 1.4. When the area over which the musicians sit is added, the total acoustical area is called S_T. To preserve loudness, the total area S_t must not be too large because the power available to each person (i.e., per unit area) is equal to the total power radiated by the total audience area S_T and the total power is not easily augmented because it increases not by adding decibels but with differential summing.

C 6.5 Conclusion: What acoustical measures should be taken

See generally (Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999).

Room acoustic characteristics can be excellent when using methods that are shown above. But no single method for obtaining the best result can be determined, because the problem lies in a properly selected model of the space.

An architect and acoustician together choose the model that will in the further steps be calculated and finally built. There is not only one model that is perfect, but there are numbers of possibilities that should be carefully chosen in this collaboration between architect and acoustician. Just a single model is just not possible because designing is a creative act. There is no perfect model because picking a model is a creative thing, just as, for example, there is no perfect artistic picture of a flower as this is also a creative act.

Side walls that provide good reflections to the center of the room yet scatter the reflection to the degree that a flutter echo does not occur are considered beneficial reflections adding to loudness and other sound field characteristics.

In a small lecture hall, reflections from both ceiling and the side walls can be designed to provide relatively uniform sound levels throughout room. The sound is heard as both louder due to the early reflections and fuller due to the reverberation than the open space conditions.

In a fine concert hall there will be reflections from an overhead ceiling canopy, strong lateral reflections from specially designed side walls, and a reverberation time of 2 s to enhance the character of music. The sound is full and spacious. It also envelops the listener. In a Gothic cathedral, with a large room volume, and all stone and glass surfaces, the sound will persist for over 4 s. Music and speech become muddy as the sound is overpowered by the reverberation and clarity is lost. The smallest difference between levels of direct sound and reflected sound should be 5 dB.

Moving reflections overhead relative to the direct signal results in increasing of loudness with no change of direction. Reflections that arrive from the sides usually increase loudness as well; but more importantly they tend to increase loudness and the sense of spaciousness.

Ceilings and sidewalls can be shaped or they can be fitted with objects that provide early reflection in the sitting area. Balcony facings and balcony ceilings can provide substantial amounts of early reflection. Big, hollow pillars, like trumpets can be placed along sidewalls to cause early reflections. They are also good for catching upper rear wall reflections and side scattering them. Softly rounded soffits placed high on the sidewalls provide a second set of early reflections. The open space above the soffits can be used for uplighting.

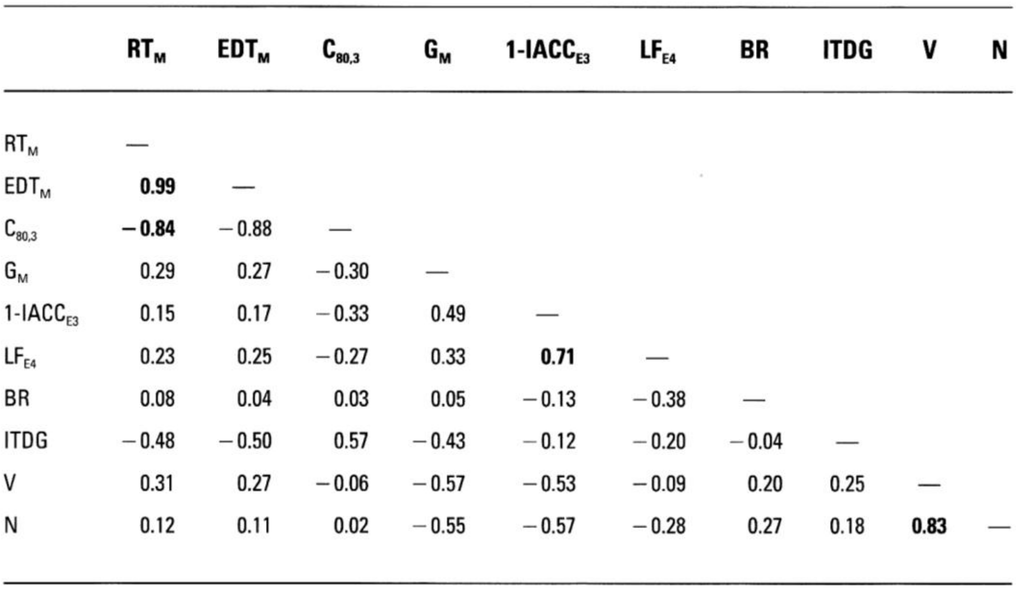
Another form of early reflection is often seen in concert halls: a suspended cloud. Suspended acoustic clouds are positioned and shaped to intercept upward-bound sound and reflect it back down into the audience area, all within the early reflection time period.

Adjustable absorption usually in the form of tracked draperies can be useful for controlling both reverberation time and loudness. Adjustable stage means that physical adjustability at the platform is desired to allow each activity to occur within an ideal stage setting. With performing area adjustability, a soloist need not perform on a large bare stage. Movable stage wall elements and batten-hung ceiling elements may be used to achieve performing area adjustability. If there is an organ it should be placed on the upstage wall and the mouths of the pipes should be high enough for choir members not to be overwhelmed by organ sound. A high ceiling is then needed with no suspended sound reflecting elements over organ.

Opera houses are halls that should produce beauty of tone for both singers and orchestra, maintain an acceptable balance of audibility between these two and produce a sense of responsiveness between he two. This is the space that should assure both reverberance and clarity. But reverberance and clarity are largely reciprocal qualities. The opportunity to reinforce voice is minimized because of the directivity of the voice. The differences between opera houses and concert halls are proscenium arch in the former separating performers from the audience, a tall fly tower behind the proscenium to permit rapid changes of scenery by flying scenery in the stage house. Concert halls are traditionally shoebox shaped while an opera house is horseshoe-shaped and the audience is in boxes at the rear and both sides, with many levels from floor to ceiling. For opera the goal was to minimize the distance from the audience to the stage. The more spacious a pit is the better the sound produced within it. In plan a pit should not be exceptionally wide and shallow.

In the following table if the correlation between two quantities is greater than about 0.6 then the quantities are dependent on each other and should not be used in judging the acoustical quality in concert halls. The table also shows that if RT is used, then EDT and C80 should not be used; in the other case, if you use volume then you should not use the number of seating places because they are highly dependent. Highly dependent means that lots of the same parameters are used in deriving the value of the objective acoustical measurement.

Figure C- 22 Correlation between major acoustical characteristics



	RT_M	EDT_M	$C_{80,3}$	G_M	$1\text{-}IACC_{E3}$	LF_{E4}	BR	ITDG	V	N
RT_M	—									
EDT_M	**0.99**	—								
$C_{80,3}$	**−0.84**	−0.88	—							
G_M	0.29	0.27	−0.30	—						
$1\text{-}IACC_{E3}$	0.15	0.17	−0.33	0.49	—					
LF_{E4}	0.23	0.25	−0.27	0.33	**0.71**	—				
BR	0.08	0.04	0.03	0.05	−0.13	−0.38	—			
ITDG	−0.48	−0.50	0.57	−0.43	−0.12	−0.20	−0.04	—		
V	0.31	0.27	−0.06	−0.57	−0.53	−0.09	0.20	0.25	—	
N	0.12	0.11	0.02	−0.55	−0.57	−0.28	0.27	0.18	**0.83**	—

Figure C- 22 Correlation between major acoustical characteristics

(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

Figure C- 23 Correlation between audible factors and acoustical factors, in general and Figure C- 24 Sound characteristics and with what measures they are gained or more detailed correlation between audible factors and acoustical factors

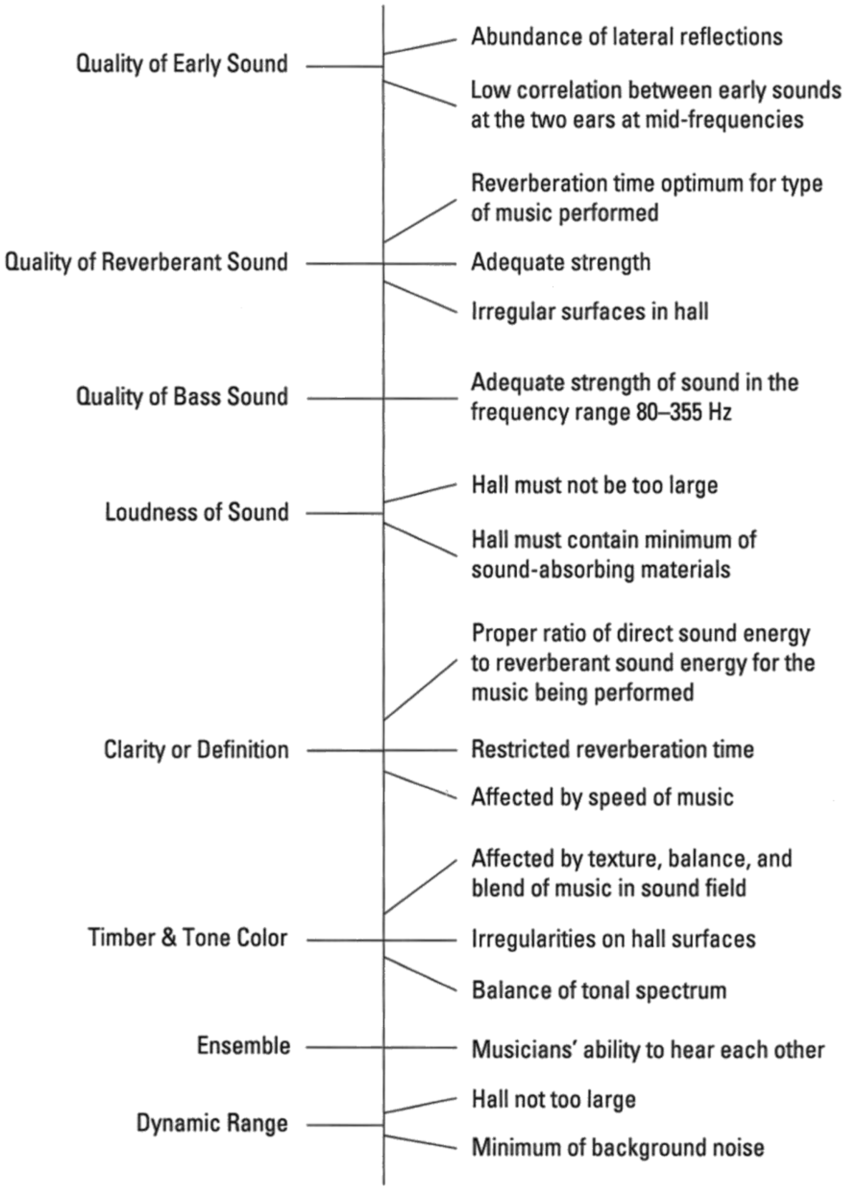
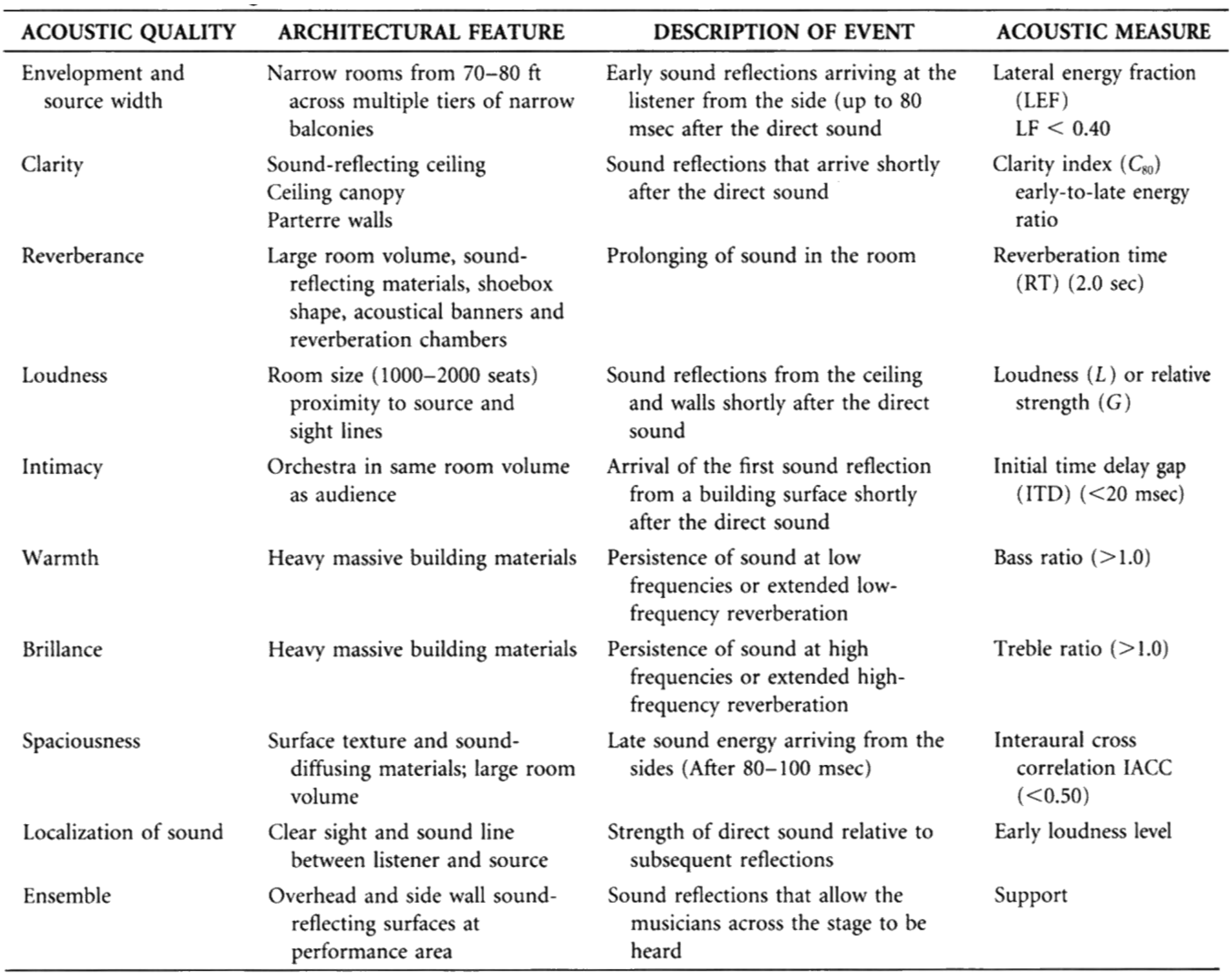


Figure C- 23 Correlation between audible factors and acoustical factors, in general
(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)



ACOUSTIC QUALITY	ARCHITECTURAL FEATURE	DESCRIPTION OF EVENT	ACOUSTIC MEASURE
Envelopment and source width	Narrow rooms from 70–80 ft across multiple tiers of narrow balconies	Early sound reflections arriving at the listener from the side (up to 80 msec after the direct sound	Lateral energy fraction (LEF) LF < 0.40
Clarity	Sound-reflecting ceiling Ceiling canopy Parterre walls	Sound reflections that arrive shortly after the direct sound	Clarity index (C_{80}) early-to-late energy ratio
Reverberance	Large room volume, sound-reflecting materials, shoebox shape, acoustical banners and reverberation chambers	Prolonging of sound in the room	Reverberation time (RT) (2.0 sec)
Loudness	Room size (1000–2000 seats) proximity to source and sight lines	Sound reflections from the ceiling and walls shortly after the direct sound	Loudness (L) or relative strength (G)
Intimacy	Orchestra in same room volume as audience	Arrival of the first sound reflection from a building surface shortly after the direct sound	Initial time delay gap (ITD) (<20 msec)
Warmth	Heavy massive building materials	Persistence of sound at low frequencies or extended low-frequency reverberation	Bass ratio (>1.0)
Brillance	Heavy massive building materials	Persistence of sound at high frequencies or extended high-frequency reverberation	Treble ratio (>1.0)
Spaciousness	Surface texture and sound-diffusing materials; large room volume	Late sound energy arriving from the sides (After 80–100 msec)	Interaural cross correlation IACC (<0.50)
Localization of sound	Clear sight and sound line between listener and source	Strength of direct sound relative to subsequent reflections	Early loudness level
Ensemble	Overhead and side wall sound-reflecting surfaces at performance area	Sound reflections that allow the musicians across the stage to be heard	Support

Figure C- 24 Sound characteristics and with what measures they are gained or more detailed correlation between audible factors and acoustical factors

(Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999)

C 6.5.1 Summary of acoustical principles in successful examples

Here is an example of one successful contemporary renovation, that of the Staatstheatre in Mainz. In beginning of the 19th century the theatre was built with a cylindrical auditorium that was slightly moved from the stage dome; it was a good example of successful acoustics.

Numerous renovations during time ruined the acoustics. The reconstruction in 21 century entailed not only going back to the original acoustics but also a room acoustical concept that would suit the needs of contemporary multipurpose functions.

These principles of renovation were used: the existing cylindrical form was divided into several reflective fields that were standing out into the space. All surfaces were inclined at angles of 30 or 45 degrees. Partition walls of half height made of Plexiglas served as reflection areas towards the auditorium. Good acoustics was aided by lifting of: parterre by 7 degrees, first range for 18 degrees, and second range for 33 degrees. Further, reflectors were fixed under the portal, that is, over the orchestra pit. Also, reflective surfaces on the front sidewalls and underneath the auditorium slab were used. For concerts, a special concert hall on stage was provided. The volume of the auditorium was extended from 5200 to 6900 m3 by prolonging the slab and opening wall behind second range. The volume per person was changed from 7.5 to 8.3 m3 per person. The furniture and cladding and facing were organized for sound requirements so that at higher frequencies they would not be unnecessarily absorbed.

In all three spaces under the dome – the hall, pit and stage – special low-frequency absorbers were incorporated. Additional absorption was installed to counteract the negative influence of the fly tower over the stage.The thesis of this dissertation is to establish whether a methodology for ensuring high quality sound can possibly be developed. In the previous section it was evident that a method does exist. Methodologies are different but they all use the same criteria or in other words limitations. It is only the question of which criterion is going to be calculated first and which one will come next. But, the element of choosing shape of the space will remain an indefinable constant. Choosing the space shape includes more elements than just demands for sound quality. When an architect chooses the shape, from that point on, the acousticians have to calculate how to get the most quality sound out of that chosen shape. And after the calculation materials can be expected to be chosen. But, designing the space is never a process of disparate steps to be taken but a very dynamic process where elements are chosen simultaneously. So, it is not an odd or unheard of situation for instance for materials to be chosen before the calculations, because of the creative demands of the architect. When speaking about methodology and whether one can be established for gaining excellent sound quality the contemporary methodology used in the process has to be discussed. An architect designs the shape of the space, and that shape then goes to acoustician for evaluation. After the shape is approved or slightly corrected by the acoustician the architect then says whether the shape of the space is going to be accepted. But this process of suggesting and approving can be very hard and long-lasting before the right decision is made. And also, in every following point there could be regression selection of the basic shape again and the process will start over from its beginnings. The following point after deciding the shape is finalizing the step of calculating criteria and after that translating those results into materials. In that finalizing step, the acousticians use computer programs to calculate the wanted criteria. The methodology for quality sound is relativised by the fact that the shape is never defined value and that it is always being questioned and frequently improved and also by the fact that materials are not decided after the calculation but often before the calculation so that it can alter the result and the process of the methodology itself significantly.

SECTION C 7 Methods_new technologies

In designing multifunctional halls the values of reverberation should differ for each function. Short reverberations are specially wanted when designing a hall that is going to be wired with loudspeakers to amplify the sound. Such places are: halls for pop concerts, musicals and similar because the acoustic characteristics for every such performance should always be the same in different halls. The conclusion is that for these types of halls the typical acoustic condition of the space is not allowed. Conditions should be obtained such that a pop concert sounds the same in a spectrum of different halls with the help of appliances for amplification. Reverberation and other characteristics can be gained with help of loudspeaker system.

One should be aware that halls for pop concerts should not be over insulated. Reverberation should not have special role in the acoustic interpretation of the space. However, even there the grade of absorption should not be too high because the electronic system cannot work in such a place, cannot be of a help if the space is too absorbent.

C 7.1 Amplification system

Loudspeakers should have the possibility to produce an extra 20 dB, for a total of 85 dB.

A good electronic sound system combined with adjustable sound absorption can be even more effective for good acoustics in the hall. Economics dictate that nearly every concert hall, theater or opera house will experience multiple uses. In recent years C. Jaffe has been a vocal proponent of electronic architecture and is responsible for the increasing acceptance of electronically synthesized concert hall sound. More recently, fine systems have been produced by Lexicon Co LAREAS and by Acoustic Control Systems ACS. Thanks to digital technology the state of the art has progressed to the point that electronically synthesized acoustics can be of exceptionally high quality, with the only major criticism being philosophical -should electronic acoustics be substituted for natural acoustics? The answer is probably in the same category as many other artificial “improvements” compared to natural origins. There is a fact that human life lasts longer thanks to civilization and the many artificial improvements of the environment. On the other hand, on a small scale, for instance with the air conditioning of spaces if outside there is a big difference in pressure, humidity and temperature, this can lead to serious health problems. The benefits of a natural environment are obvious. In performance halls that are not too large artificial help is not of major importance because with good design good acoustics can be achieved. In large auditoriums amplification of the sound cannot be avoided, and most of the sound energy will come through an amplifying system. The conclusion should be that if artificial resources are used then it is at least necessary to understand and obey human limits. Here there is a word about architects and ordering acoustic studies of the hall and cooperation with acoustical professionals. Studios can be designed as very live to use natural characteristics of the space and the sound produced that way is further taped and manipulated or totally absorbent to totally avoid implementation of space characteristics and in second step the sound is enriched electronically with sound characteristics.

C 7.2 Computers in acoustics

See generally (Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999).

The best method of determining BQI before construction is the making of a computer model. Computer models are important in the early stages of design because they can trace out the first 20 early reflections fairly accurately. From the model, acoustical reflectograms can be obtained that indicate the number and spacing (relevant for texture) of the early reflections. For greatest accuracy, a wooden model, on a 1/10 or 1/20 scale is the best. The frequencies produced by the sound source must be increased by the scale of a model; further, materials that have an adequate coefficient to the new enlarged frequency should be used. For instance in a 1:10 model when simulating concrete the material used would have to have an absorption coefficient of 0.01 at 10 000 Hz. This is because the direct sound is scaled 10 times and for mid frequency of 1000 in a 1:10 model, 10000 would be used. Acoustical models have been developed to represent accurately the sound obtained at individual seating locations in a hall. Acoustical model have been evaluating from real model to computer model. Computers allow change of design in the early phase of a project and models allow the possibility to really hear the sound before the hall is actually built and to add details to get better texture, brilliance and other features of a sound field. Such investigation allows architects and acoustical consultants ore easily to sculpt the acoustical qualities of a room in the design presses. As the frequency used in a real model increases from 1000, representing the mid frequencies, to 10000 in a real model in scale of 1:10 the air influence becomes much more absorptive. Therefore, in small size models, nitrogen is used instead of air, or very dry air with less than 3% of humidity, or mathematical correction is employed in the subsequent computer measuring. Computer models are three dimensional models such as CAD models that can be further imported into the acoustical program. The computer calculates the impulse response of the room. In acoustical programs one can choose the direction and frequency of the sound. After that the program calculates the arrival time and the amplitude of reflected sound for the selected location in the model. The room surfaces are assigned absorption coefficients in octave band frequencies. Many current programs also can approximate the diffusion and diffraction. Some programs also provide the reading of an envelope derived from reverberation. Computer models show the distribution of sound pressure levels in the room, ray diagrams between source and listener and many other acoustical parameters. A miniature loudspeaker can be moved around on the stage to represent the different sections of an orchestra and a small sphere with miniature microphones on two sides representing ears can be used to represent a listener. After generating a computer model and 1:10 scale model one would like to actually hear how the sound is really heard and this is done by converting the response into aurally simulated sound. An anechoic environment does not add any sound reflections or reverberations to the sound source. This is called dry recording. The listener can be moved about the sitting areas in the model and BQI can be measured accurately.

The industry that produces absorption materials will very often provide programs to calculate reverberation in the form of free software based on excel tables. More complicated programs are CATT-Acoustics and for instance ODEON. There has been some research into how the auralization in a model compares to real sound in a hall. Results show that, objectively, differences in sound pressure level SPL, T30 and C80 were negligible in the majority of cases. Subjects did not perceive any differences when comparing the auralizations. The program also calculates reverberation, clarity and realism. An important advantage of a real model is that the balcony fronts, wall diffusion, and irregularities throughout the room can be adjusted both to satisfy the architect's visual demands and to obtain uniformity of BQI over the sitting areas. In this method, a person using earphones can actually hear the sound as it would be heard in the completed hall. Any new design, especially any radical design, should be modeled early in the project's life. A computer model is most desirable at the beginning stage, and it can be changed or discarded and an entirely new approach considered, without a great loss in time or cost.

An acoustical consultant can look at an impulse response and make diagnoses about the acoustical health of the room and recommend design changes. The impulse response can help provide a conceptual understanding of the link between perceived acoustical qualities and the actual architectural features of the room. It is used extensively to characterize sound field both in computer models, scale models and full size rooms.

Experienced acoustical consultants should be engaged with the joint approval of the investor and architect. Use of a computer to model a hall is almost essential today, because various architectural designs can be studied and absolute failure prevented. For complete assurance before construction, a 10:1 or 20:1 wooden model will enable final shaping of balcony fronts, rear wall designs, proper cubic volume and sight lines. If it is financially possible to involve an experienced acoustical consultant into the project and computer designed acoustics and modeling of the hall, it is highly recommended to do so. These steps are costly, but in no way as costly as post construction changes These steps are costly, but in no way as costly as post construction changes. Computer usage significantly forms the contemporary methodology for getting quality sound. Computers provide the possibility to question the shape and materials many times in the design process. But, at the same time the computer relativises the results because better results are always possible. A better result means that criteria are every time nearer to wanted value but it can also mean that one of the criteria is getting to the other side of the wanted value scale. So, in the process of computer calculation criteria should be estimated by acoustician to preserve wanted quality of sound. This estimation is also a creative process because results can be calculated an indefinite number of times. When the term creativeness apperas in the search for a methodology, any thesis aimed at establishment of a methodology for the production of high quality sound has obviously been negated.

SECTION C 8 Methodology according to the function of the space

C 8.1 Methodology in halls with vocal performances

See generally (Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.).

To examine the relationship between the orchestra and human voice the logical step is to know the acoustics of opera houses. In these spaces the focus is definitely mostly oriented to the human voice and this perception is meaningful for comprehending a multifunctional hall or variable acoustics.

THEATRES Proscenium theaters with a capacity up to and exceeding 1000 seats are possible without electronic amplification. But theaters-in-the- round require amplification above 600 seats. In theatres the proscenium is best served with a moderate fan-shaped auditorium. Because being as close as possible is important in theatres, a plan with balconies is always better. A high ceiling is not practical because the goal of intelligibility demands lower reverberation. This is best met by a low ceiling that reflects sound quickly to the audience, no later than 30 ms after the direct sound. Under-balcony soffits can provide reflection for the seats under the balcony. The Alley Theater in Huston, Texas is a good example of theater acoustic design. It is a mildly fan-shaped plan, with a steep floor and a relatively low ceiling shaped to reflect sound from the stage directly to the audience with minimum delay. The rear wall surfaces have an efficient sound absorbing treatment of carpet over glass fiber. The reverberation time is 1 s, unoccupied, and only slightly lower when occupied since upholstered seats compensate for the missing audience.

Opera originated in Italy in courts at the end of the 15th century, but opera as we know it came to life a hundred years later in a Florentine palace, evolving from a collection of short vocal pieces with melodies that were accompanied by instrumental chords (recitativo). The first opera was staged in Florence 1589 - *Dafne* by the poet Rinuccini set to music by Jacopo Peri. The first opera house was the Teatro di San Cassino that opened in Venice in 1637. The second-oldest standing opera house in Italy is Teatro alla Scalla that opened in August 1778.

Figure C- 25 Italy, Milan, Teatro alla Scalla inside view and Figure C- 26 Italy, Milan, Teatro alla Scalla, plan and section

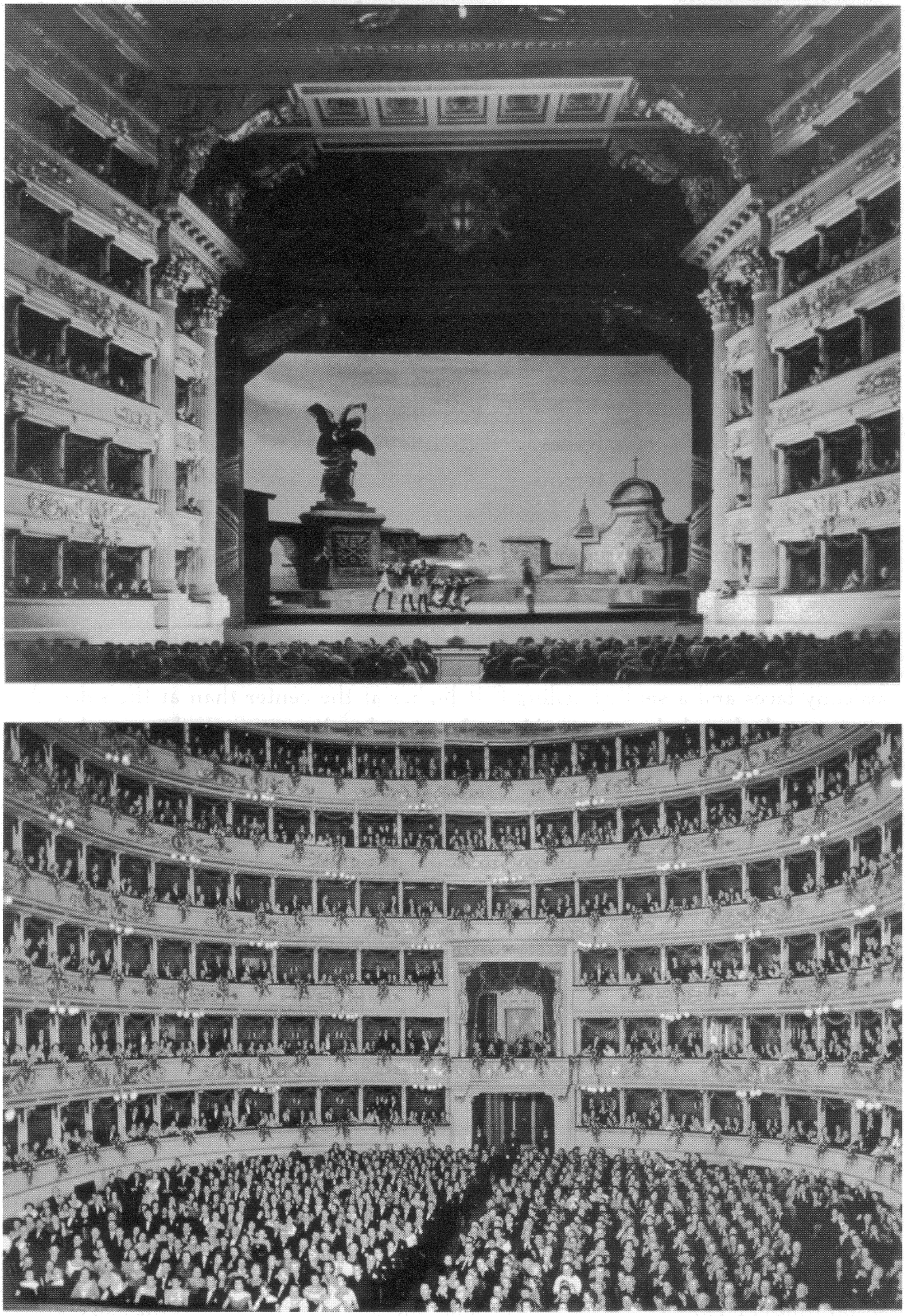


Figure C- 25 Italy, Milan, Teatro alla Scalla inside view

(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

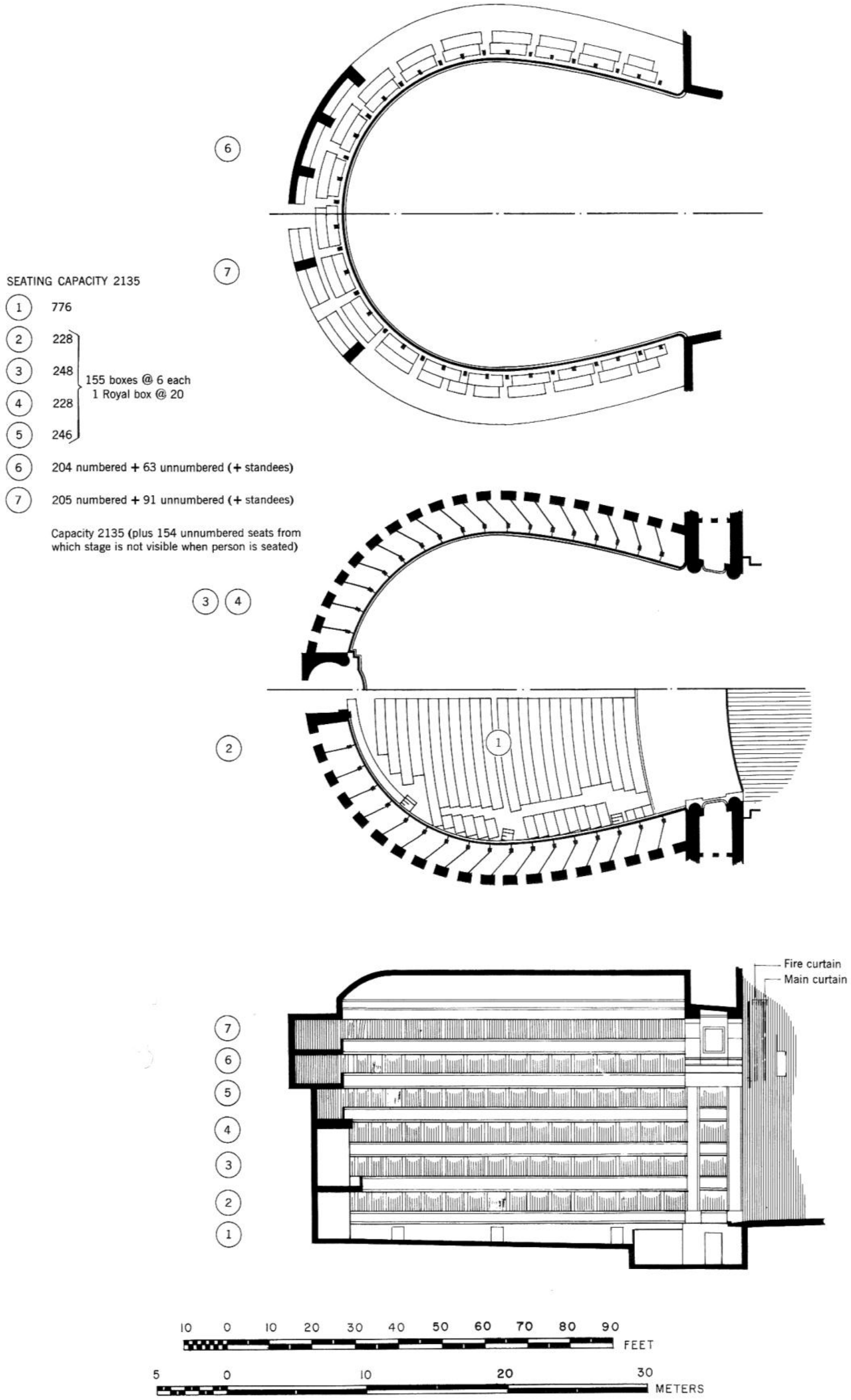


Figure C- 26 Italy, Milan, Teatro alla Scalla, plan and section

(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

In the mid-18th century, opera flourished in Paris under Louis XVI. The royalty and members of the cabinet sat in boxes at the sides of the stage. There were three levels of boxes, usually in a horseshoe plan, with partitions between so that patrons had to stand to see the stage. Those in the parterre had the misery of standing up for four hours. In the 19th century Paris fostered grand opera with elaborate scenario, costumes, and large orchestras. In 1875, France's famous Opera Garnier was opened.

In questionnaires in which 22 world important opera conductors participated, acoustical quality in the audience area in world opera houses was rated. It was found out that the five best opera houses are: in Buenos Aires, Dresden, Milan, Tokyo and Munich. The conductors were also asked: What mostly makes you judge the sound in some opera houses better than in others: Their answers were: 1) the hall support singers, 2) uniformity of singer projection from a wide area on the stage, 3) good balance between orchestra and singer, 4) clarity and richness of orchestral and singing tones. In Italian opera the intimacy and clarity of both the singers and the orchestra are important, and that is why horseshoe shaped halls of compact size with an open pit and relatively low reverberation times are necessary.

These characteristics named by famous conductors, should for acoustical purposes, be further explained:

1) SIZE AND SHAPE With a large number of seats, assuming evenly distributed sound, there is less soloist energy per person. For the architect, a large house with modern seats occupying a large area per person necessitates special construction around the proscenium to project voices efficiently to the audience areas. The acoustical measurement in the Tokyo New National Theatre Opera House indicates that the horseshoe shape is not necessary to obtain a good opera house; indeed the shape is outperformed by the Tokyo New National Theater. Visual factors certainly have entered into the decisions to build tiered, horseshoe shaped houses, because the construction reduces the distances between the stage and most of the listeners compared to those distances in conventional auditoriums. The negative feature of horseshoe shaped houses is that the vision from the boxes nearest the stage is usually bad. Something more should be said about this relatively new opera house from 1997, with 1810 seats, that catapulted Japan to the cultural center of the world. The architect Takahiko Yanigasawa said: "The design of the Opera House facilitates the exchange of energies between those on stage and those attending the performance... The people in the audience are positioned so that they surround the stage as much as possible, and the balconies encourage empathy amongst them..." To achieve the goal of excellent acoustics, acoustical trumpets were designed, which means that the projection of the singers' voice sound levels is higher than in conventional horseshoe-shaped operas. The Tokyo New National Theater is designed as a conventional theater with three shallow balconies and with special trumpets at the front of the main floor and each balcony to enhance the strength of the singer's voice. The overhead sound reflector supplies the necessary clarity. The balcony front trumpet assures optimum spaciousness and loudness. Also, the balcony faces are shaped to provide early lateral reflection, to aid in uniform sound distribution, and to increase the loudness. The reverberation time, occupied, at mid frequencies, is 1.5 s.

2) BQI, QUALITY INDEX measured by ($1-IACC_{E3}$) has the highest correlation of the physical measures with the subjective judgments of acoustical quality rated by conductors in opera houses. Binaurality defines spaciousness in the hall. And surprisingly, the more

the difference between the sound collected by the two ears, the more greater the space seems to us, and correlatively the greater the music, to our brains this means that the music is loud, which we appreciate: the effort, the energy...The measurement of BQI in the best opera houses is 0.6.

3) INTIMACY, THE INITIAL-TIME–DELAY GAP (ITDG) is given by measuring early lateral reflections. The best houses have ITDG of 20 ms or less.

4) REVERBERATION in opera houses should be in a range from 1.4 to 1.6 s. The highest rated opera house in the world, the Buenos Aires Teatro Colon, has a RT_{OCCUP} equal to 1.6 s. For Italian opera alone, 1.4 s is best.

5) CLARITY is C80; in an opera house this is so highly correlated, , with the reverberation time that it cannot be used as an additionl way to estimate the acoustical quality of an opera house.

6) STRENGTH FACTOR, G_{mid} and G_{125}.For excellent acoustics in opera houses, good texture of sound is necessary; this is accomplished with sidewall reflection to push the early sound directly to the audience. G_{mid} should be greater than 1 dB and G_{125} shold be about 2 dB.

7) TEXTURE. Good texture requires a large number of early reflections, reasonably strong in amplitude, uniformly but not precisely spaced apart, and with no single reflection dominating the other, which is gained through relief texture of reflective areas

8) ORCHESTRA PITS The musicians in the pit should be able to hear other sections of the orchestra without the undesirably long time delays that result from too long a pit, and the musicians also need to hear the singers in order to maintain good ensemble playing. It is also necessary for the singers and players to see the conductor easily. The music for non-Wagnerian operas should have good balance between orchestra and the singer, as well as blend, which means making harmony, without tonal distortion. It is more important that singers and players hear each other than see each other and this favors the open pit, neither too deep nor overhung. For Wagnerian operas, for a dramatic outcome, the mystical sound from an invisible orchestra is an important element. In that sense there are three types of orchestra pits: 1. open pit, for example Vienna Staatsoper, which is good for communication between singers and musicians while an objection to it is the disturbing visual effect on the audience in the upper rings. The second objection is that 7 to 9 meters is very great distance between the audience and the stage. This is perhaps good because an audience ought not to be directly next to the stage. The pit's depth is usually between 2.5 to 3.5 m, and for singers the best position of the orchestra is 30 cm below the level of the stage. A slight overhang of the pit by the forestage is not objectionable acoustically and has the advantage of increasing the reflecting area of the stage between the singers and the audience, a very desirable feature in large hall, but it should be no more than 1 m. 2. Sunken pit, the Bayreuth Festspielhaus.

Figure C- 27 Germany, Bayreuth, Festspielhaus, inside view and Figure C- 28 Germany, Bayreuth, Festspielhaus, plan and section

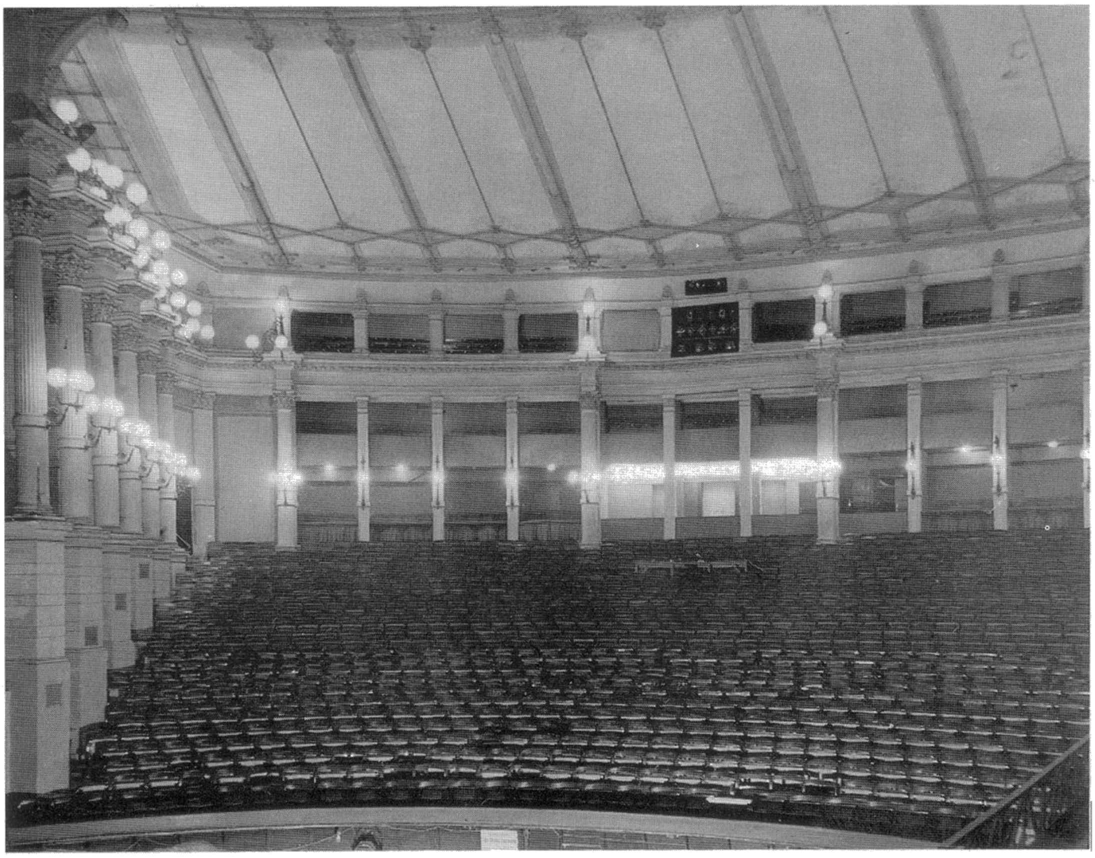


Figure C- 27 Germany, Bayreuth, Festspielhaus, inside view

(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

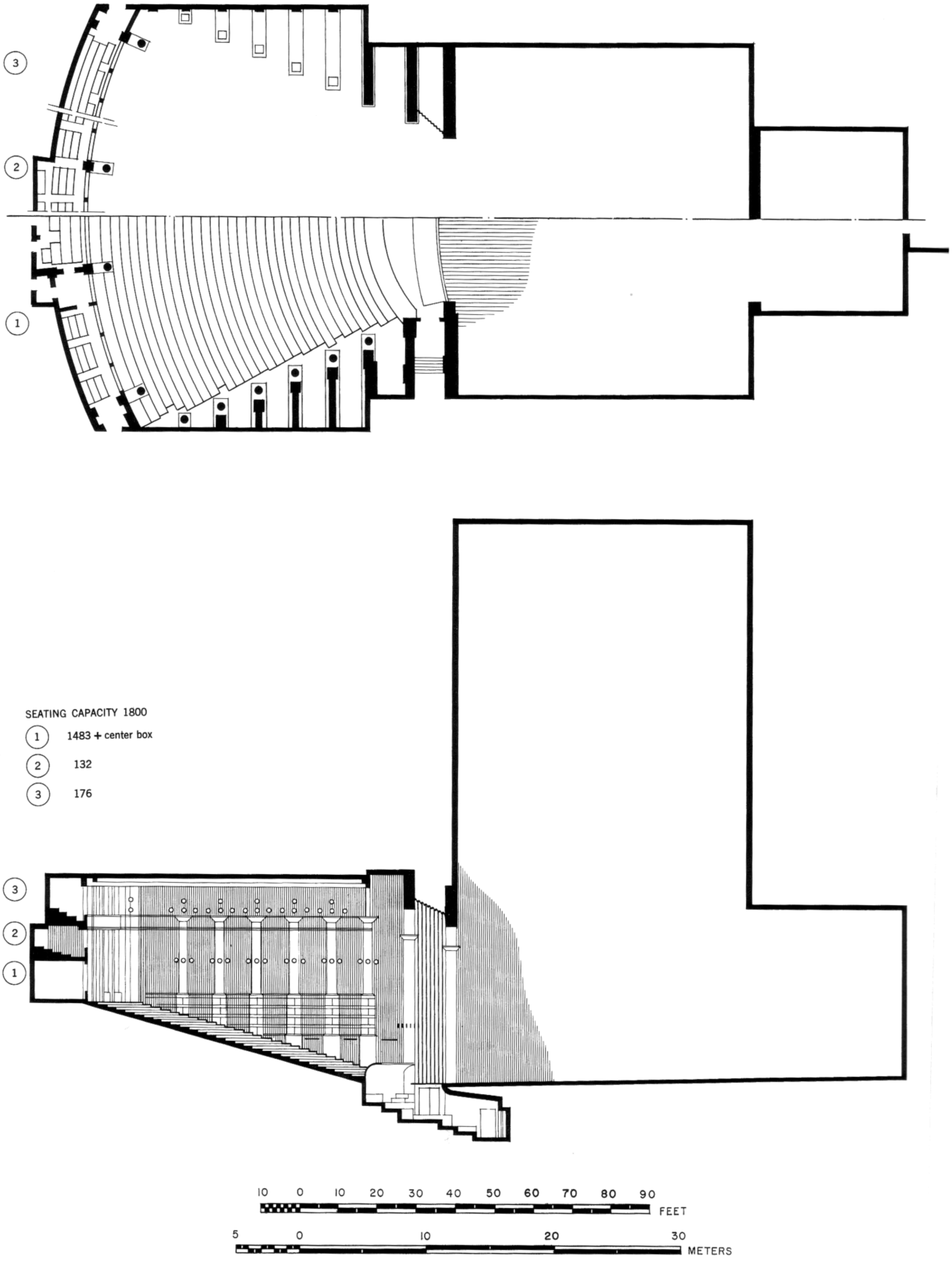


Figure C- 28 Germany, Bayreuth, Festspielhaus, plan and section

9) It is partly buried beneath the stage and the remaining portion is nearly completely covered by an overhang. Except for Wagner's music, the Bayreuth pit is not considered

satisfactory because the string tones are muffled and the orchestra takes on an eerie sound., 3 Sunken pit , open, an example of which is the Eastman Theatre in Rochester; generally those pits are of only moderate success. The floor area is usually at least twice as great as the open area.

10) BOXES AND BALCONIES Boxes were originally constructed to be a frame for their inhabitants, the listeners at the box openings and further to the main floor. Visually, some opera house boxes have a mirror on the farthest wall from the stage. Listeners sitting back in the boxes on the sides of a horseshoe shaped hall do not enjoy great acoustics. In the Philadelphia Academy of Music, the partitions between boxes have been moved, so that everybody enjoys good sound and view.

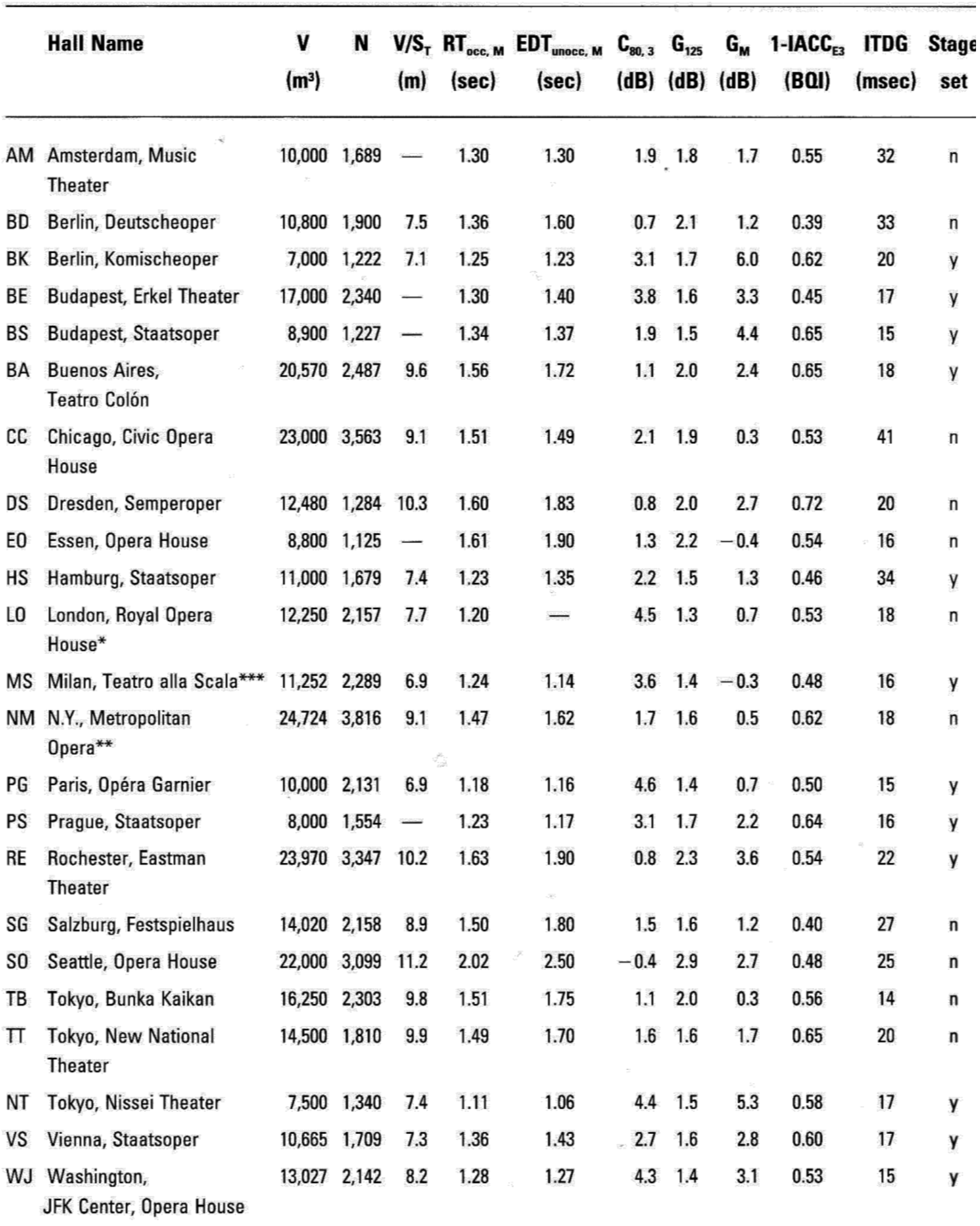
11) BALCONIES Reverberation is less important in an opera house than in a concert hall. Thus, balcony overhangs are less of a problem, a because listener’s attention is focused more on the intelligibility of the voice. Two general recommendations are: 1. the distance D should not exceed twice the height H. In addition, the balcony soffit and rear and sidewalls should be shaped to reflect the direct and early lateral reflections to the heads of the listener. As a more sensitive measure than the D over H ratio, the angle θ (theta) should preferably be 25 degrees or greater.

12) ECHO In opera houses, a small echo heard on the stage by a singer may be desirable, while the same echo heard on the stage of a concert hall might be mildly troublesome to the players. The rear wall of the main floor, which otherwise may return too strong a reflection, can be “toned down”, by adding sound-absorbing materials to it or by tilting it backward. The sound –absorbing material can be in the range from 1.9 to 2.5 cm thick and should be placed behind removable, acoustically transparent screen so that varying amounts of it can easily be added. Such a thickness will absorb frequencies of 500 Hz or higher. If the decision is to tilt the backstage wall backwards then sound absorbing material should be placed on the underside of the balcony (soffit) so that the wave is reduced before its reflection to the soloist on the stage. Okano made a measurement of that kind in 1994 and established the values of 120,170,220 ms, which means that reflecting surfaces 21, 29 and 38 m distant should be 36, 38 and 42 dB below the direct sound.

13) DISTORTION should be avoided and it means avoiding selective sound absorption by some surfaces or by the seats. For example: protective sprays applied to the underside of the fabric upholstery covering should not be permitted, because with it, the seats would reflect much more sound when unoccupied than occupied, in that way making rehearsals more difficult. Also focusing the sound to certain parts of the hall’s should be avoided. Resonance from grillwork in front of ventilation ducts is also potential distortional problem..

Conclusion: for opera houses it is important to obtain a high value of binaural quality index (BQI), a short Initial-time-delay-gap (ITDG) and a good texture.

Figure C- 29 Example of acoustically successful opera houses and their gained values

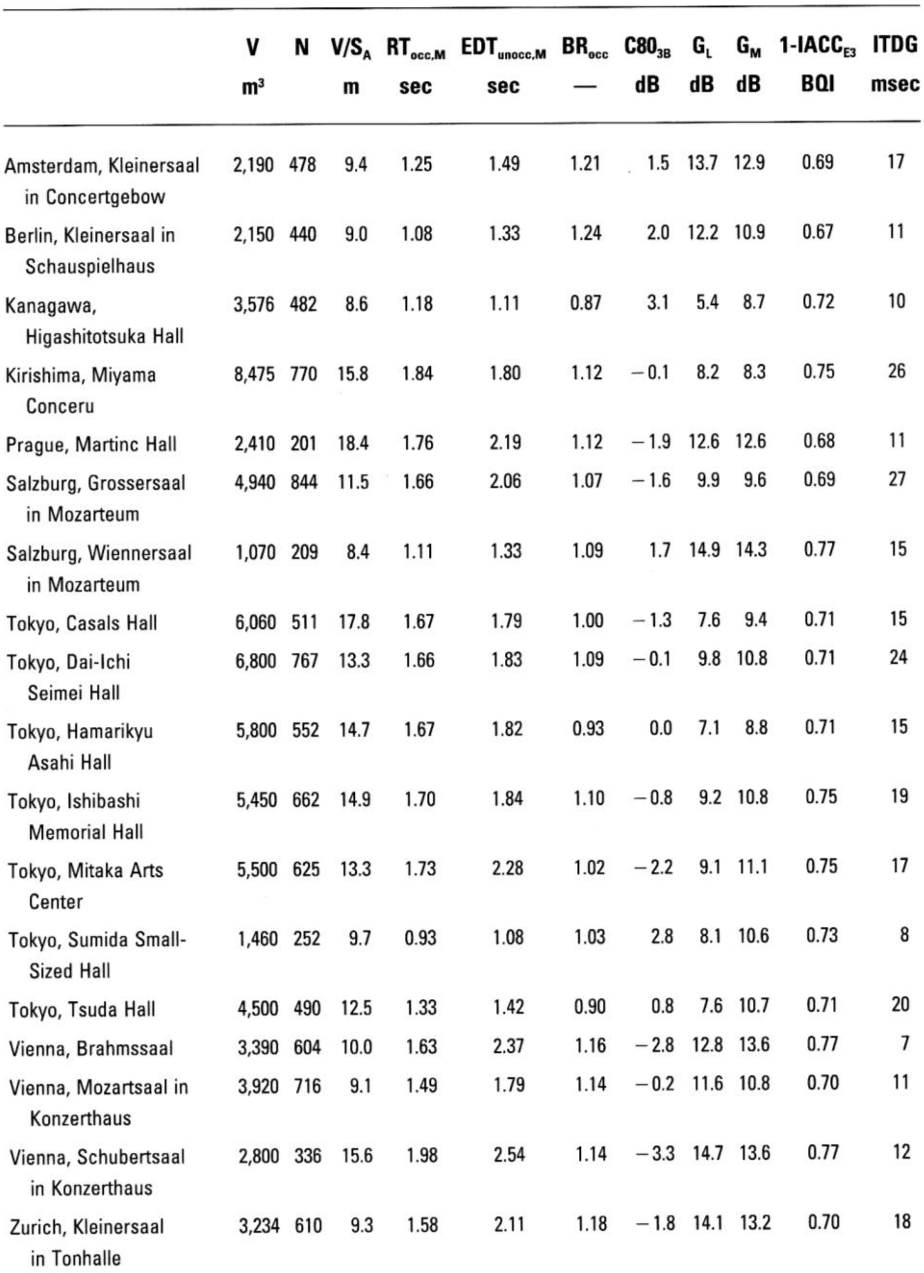


	Hall Name	V (m^3)	N	V/S_T (m)	$RT_{occ, M}$ (sec)	$EDT_{unocc, M}$ (sec)	$C_{80, 3}$ (dB)	G_{125} (dB)	G_M (dB)	$1\text{-}IACC_{E3}$ (BQI)	ITDG (msec)	Stage set
AM	Amsterdam, Music Theater	10,000	1,689	—	1.30	1.30	1.9	1.8	1.7	0.55	32	n
BD	Berlin, Deutscheoper	10,800	1,900	7.5	1.36	1.60	0.7	2.1	1.2	0.39	33	n
BK	Berlin, Komischeoper	7,000	1,222	7.1	1.25	1.23	3.1	1.7	6.0	0.62	20	y
BE	Budapest, Erkel Theater	17,000	2,340	—	1.30	1.40	3.8	1.6	3.3	0.45	17	y
BS	Budapest, Staatsoper	8,900	1,227	—	1.34	1.37	1.9	1.5	4.4	0.65	15	y
BA	Buenos Aires, Teatro Colón	20,570	2,487	9.6	1.56	1.72	1.1	2.0	2.4	0.65	18	y
CC	Chicago, Civic Opera House	23,000	3,563	9.1	1.51	1.49	2.1	1.9	0.3	0.53	41	n
DS	Dresden, Semperoper	12,480	1,284	10.3	1.60	1.83	0.8	2.0	2.7	0.72	20	n
EO	Essen, Opera House	8,800	1,125	—	1.61	1.90	1.3	2.2	−0.4	0.54	16	n
HS	Hamburg, Staatsoper	11,000	1,679	7.4	1.23	1.35	2.2	1.5	1.3	0.46	34	y
LO	London, Royal Opera House*	12,250	2,157	7.7	1.20	—	4.5	1.3	0.7	0.53	18	n
MS	Milan, Teatro alla Scala***	11,252	2,289	6.9	1.24	1.14	3.6	1.4	−0.3	0.48	16	y
NM	N.Y., Metropolitan Opera**	24,724	3,816	9.1	1.47	1.62	1.7	1.6	0.5	0.62	18	n
PG	Paris, Opéra Garnier	10,000	2,131	6.9	1.18	1.16	4.6	1.4	0.7	0.50	15	y
PS	Prague, Staatsoper	8,000	1,554	—	1.23	1.17	3.1	1.7	2.2	0.64	16	y
RE	Rochester, Eastman Theater	23,970	3,347	10.2	1.63	1.90	0.8	2.3	3.6	0.54	22	y
SG	Salzburg, Festspielhaus	14,020	2,158	8.9	1.50	1.80	1.5	1.6	1.2	0.40	27	n
SO	Seattle, Opera House	22,000	3,099	11.2	2.02	2.50	−0.4	2.9	2.7	0.48	25	n
TB	Tokyo, Bunka Kaikan	16,250	2,303	9.8	1.51	1.75	1.1	2.0	0.3	0.56	14	n
TT	Tokyo, New National Theater	14,500	1,810	9.9	1.49	1.70	1.6	1.6	1.7	0.65	20	n
NT	Tokyo, Nissei Theater	7,500	1,340	7.4	1.11	1.06	4.4	1.5	5.3	0.58	17	y
VS	Vienna, Staatsoper	10,665	1,709	7.3	1.36	1.43	2.7	1.6	2.8	0.60	17	y
WJ	Washington, JFK Center, Opera House	13,027	2,142	8.2	1.28	1.27	4.3	1.4	3.1	0.53	15	y

Figure C- 29 Example of acoustically successful opera houses and their gained values (Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

C 8.2 Methodology in chamber concert halls with a seating capacity of less than approximately 800

Figure C- 30 Examples of acoustically successful halls with seating capacities of less than 800 and their gained values. EDT unoccupied The preferred values given in the table assume that the chairs are medium upholstered. With leather upholstering or with many chairs in the hall not upholstered, EDT will be longer.



	V m^3	N	V/S_A m	$RT_{occ,M}$ sec	$EDT_{unocc,M}$ sec	BR_{occ} —	$C80_{3B}$ dB	G_L dB	G_M dB	$1\text{-}IACC_{E3}$ BQI	ITDG msec
Amsterdam, Kleinersaal in Concertgebow	2,190	478	9.4	1.25	1.49	1.21	1.5	13.7	12.9	0.69	17
Berlin, Kleinersaal in Schauspielhaus	2,150	440	9.0	1.08	1.33	1.24	2.0	12.2	10.9	0.67	11
Kanagawa, Higashitotsuka Hall	3,576	482	8.6	1.18	1.11	0.87	3.1	5.4	8.7	0.72	10
Kirishima, Miyama Conceru	8,475	770	15.8	1.84	1.80	1.12	−0.1	8.2	8.3	0.75	26
Prague, Martinc Hall	2,410	201	18.4	1.76	2.19	1.12	−1.9	12.6	12.6	0.68	11
Salzburg, Grossersaal in Mozarteum	4,940	844	11.5	1.66	2.06	1.07	−1.6	9.9	9.6	0.69	27
Salzburg, Wiennersaal in Mozarteum	1,070	209	8.4	1.11	1.33	1.09	1.7	14.9	14.3	0.77	15
Tokyo, Casals Hall	6,060	511	17.8	1.67	1.79	1.00	−1.3	7.6	9.4	0.71	15
Tokyo, Dai-Ichi Seimei Hall	6,800	767	13.3	1.66	1.83	1.09	−0.1	9.8	10.8	0.71	24
Tokyo, Hamarikyu Asahi Hall	5,800	552	14.7	1.67	1.82	0.93	0.0	7.1	8.8	0.71	15
Tokyo, Ishibashi Memorial Hall	5,450	662	14.9	1.70	1.84	1.10	−0.8	9.2	10.8	0.75	19
Tokyo, Mitaka Arts Center	5,500	625	13.3	1.73	2.28	1.02	−2.2	9.1	11.1	0.75	17
Tokyo, Sumida Small-Sized Hall	1,460	252	9.7	0.93	1.08	1.03	2.8	8.1	10.6	0.73	8
Tokyo, Tsuda Hall	4,500	490	12.5	1.33	1.42	0.90	0.8	7.6	10.7	0.71	20
Vienna, Brahmssaal	3,390	604	10.0	1.63	2.37	1.16	−2.8	12.8	13.6	0.77	7
Vienna, Mozartsaal in Konzerthaus	3,920	716	9.1	1.49	1.79	1.14	−0.2	11.6	10.8	0.70	11
Vienna, Schubertsaal in Konzerthaus	2,800	336	15.6	1.98	2.54	1.14	−3.3	14.7	13.6	0.77	12
Zurich, Kleinersaal in Tonhalle	3,234	610	9.3	1.58	2.11	1.18	−1.8	14.1	13.2	0.70	18

Figure C- 30 Examples of acoustically successful halls with seating capacities of less than 800 and their gained values

(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

C 8.3 Methodology in concert halls

In the beginning of this section some basic features evolved through the past should be explained. We are nowadays very impressed with ancient history, and consider that this was a time in which excellent acoustics were produced. In following paragraphs this will be considered and the myth will be explored.

Ancient theatres can be divided into two groups. Amphitheatres, still open for the public today and suitable for lots of people, about 7000; and the other group, containing closed theatres called

Odeons that could accommodate 2000 visitors. The acoustics of the open amphitheatres were in comparison to present-day acoustics rather poor, but in the closed Odeon they were the same as current concert halls for concerts. Amphitheatres had reverberation of 1.8 s in mid frequencies and in low frequencies a 0.5 s longer reverberation. The strength is between 0 and -7dB which is lower than average, which should not be lower than +3dB in concert halls of today. Odeons did not have absorptive materials except audience because they were mostly made of marble and the reverberation time was about 1.5 and a strength G of about +6dB. In higher frequencies air and audience reduced reverberation.

AMPHITHEATER DESIGN. For amphitheater designing it is important to provide: 1 a suitable environmental noise level; 2 site conditions for the performers, and the following should be taken into consideration: walls, berms to shield the audience from noise intrusion and that means a performing area surrounded on three sides and overhead by sound reflecting surfaces is most desirable for musical groups. A well designed enclosure provides good instrumental blending and balancing and provides on stage hearing conditions for good ensemble playing and good microphone pick up conditions. Also, weather protection is also a major consideration; 3 hearing and viewing conditions for the audience. This means having an unobstructed line of sight onto the performers and loudspeakers. A steeply sloped area for the audience is the best. With a flat audience area, the performers must be elevated to be seen. Loudspeakers should not be elevated more than 13.5 m because of echo delay problems. It is a greater problem to conduct the sound from the loudspeaker that is near the stage to flat-positioned auditorium than when distant listeners are elevated. The conclusion about the relation between current concert halls and ancient Greek and Roman structures is that ancient acoustics were of lower quality, but regardless to that fact we like to think, with romantic and nostalgic admiration, that ancient acoustics were superior.

The same admiration holds for opera theatres of the 19th century that in general have excellent acoustics due to lots of detailing and, because of this, a lot of quality scattering and diffuse field. The admiration is again supported by our nostalgic view of this historical period.

When designing the performance hall the first thing to begin with should be that the source must be adequately loud at all possible listener locations. This is accomplished by taking advantage of the natural reinforcement of the room surfaces that reflect the sound from the source to the listener.

In larger rooms electronic reinforcement system must supplement the natural loudness of the desired sound. In very large auditoria and sports arenas, an electronic amplification system as described in one of following chapters does the entire job of providing adequate loudness.

Another requirement associated with the loudness requirement is that the desired sound must be distributed uniformly throughout the listening space without long delays, discrete reflections, echo, focused reflections, repetitive reflections or flutter echoes, standing waves or other undesirable changes of the original source. In general, reflected signals that arrive within the first 40 ms after the direct sound contribute to the apparent loudness of the sound. Reflected sounds that arrive after 60 ms may be distinguished as discrete separate signals or echoes. Intermediate delays between about 40 and 60 ms may simply result in fuzziness of the sound received with no real contribution to its loudness or intelligibility. A final requirement for good listening conditions is adequate reverberation control. Too long and too loud reverberations can destroy speech intelligibility, and on the other side inadequate, too short and too quiet reverberations can make the sound dead and lifeless.

1) Reverberation time according to rank ordering based on questionnaires involving conductors, critics and concert aficionados is 2.0 s for symphonic music. Reverberation time for organ music is between 3 and 5 s. If a separate rehearsal space is to be provided, the optimum reverberation time should be 0.2 to 0.4 s, so that musicians can hear every note and nuance during rehearsal. The EDT unoccupied approximately equals RT occupied times 1.15 to 1.2 in modern halls with medium upholstering. Early Decay Time for the best halls is between 2.25 to 2.75 s and it is rather dependent on whether the hall is occupied or unoccupied. That dependence for low frequencies is about 15 percent, for mid-frequencies 30 percent and for high frequencies around 50 percent. For unoccupied halls, at all frequencies the early decay times EDT are almost exactly the same as the reverberation times RT.

2) Binaural quality Index BQI is one of the most effective indicators of the acoustical quality of concert halls. It is a measure of the difference in the musical sounds that reach the two ears within 80 ms after arrival of the direct sound and should measure 0.6 or more. The BQI is impressively effective in rating the acoustic quality of a concert hall, provided the other important acoustical parameters are within reasonable limits, that is to say, the reverberation time at mid-frequencies, fully occupied, lies between 1.7 and 2,1 s, the initial-time-delay gap is less than 35 ms, there is a satisfactory bass response, the hall is not too large so the loudness is satisfactory, and the hall has irregularities on the wall and ceiling so that the reverberant sound field is pleasant. BQI depends on abundance of early lateral reflections. Its value can be crudely estimated from architectural drawings if careful consideration is given to the first 10 to 15 early sound reflections. Another outstanding feature of BQI is that it permits one to estimate acoustical quality even when it is measured in an unoccupied hall because the ratio between unoccupied and occupied is 10 percent.

3) Warmth, Bass Ratio (BR) and Bass STRENGTH (Glow) can be measured in three different ways: 1. but not accurately enough, as Bass Ratio (BR) and it is the ratio of the Reverberation time (RT) in occupied halls at low frequencies to those at mid-frequencies.2. Measuring the strength of the bass sound by the formula:$(G_{125}+G_{250})-(G_{500}+G_{1000})$ was also not very useful. 3.The only measure that was satisfactory for measuring the warmth of the sound was measuring G_{125} in decibels in unoccupied halls and should be between 3 and 5 dB. G_{125} is then 1.2 dB for occupied halls. Lightly upholstered halls should not be measured as unoccupied hall because people absorb more than 1.2 dB. Bass ratio based on early decay time, BR (EDT) is BR (RT) =low frequency reverberation time (125 and 250Hz)/middle frequency reverberation time (500 Hz and 1 kHz).

4) Intimacy, Initial-time-delay-gap (ITDG) is usually quoted for an audience position near the center of the main floor, halfway between the stage front and the first balcony front, or the rear wall if there is no balcony. The first reflection in shoebox halls usually comes from a

balcony front, or otherwise from a lower side wall. In the fan shaped hall the first reflection may come from suspended panels or the ceiling. In most high ranked halls the average ITDG is about 30 ms. In the best concert halls and opera houses the ITDG is less than 25 ms. Superior results are 20ms. In a very large hall, particularly one fan shaped, the initial-time-delay-gap is as high as 55 ms. It is not too difficult to obtain a reasonable ITDG in a hall that is not too large, provided it is not fan shaped. Tanglewood Music Shed and Venezuela, Caracas, Aula Magna are both fan shaped, so that there is minimum of lateral reflections. After the introduction of horizontal suspended panels, this reduced the ITDG from 45 to 19 ms. So, it is important to have reflecting surfaces near the proscenium like as in the Tanglewood Music Shed or sound reflecting panels, equal in area to about 70 percent of the ceiling and hung below the ceiling and on the side walls.

5) LOUDNESS of the music largely relates to G mid and can be too little, or too great, as in halls seating less than 1000. G mid is related to the early decay time $EDT_{UNOCCUPIED}$ divided by the cubic volume V. The EDT unoccupied approximately equals RT occupied times 1.15 to 1.2 in modern halls with medium upholstering. In some halls, large reflecting panels around the upper part of the hall send a large part of the early sound directly to the audience, making the levels of G_{MID} higher than would be expected from the ratio EDT/V. G mid for the best halls lies between 2 and 5 dB.

6) ACOUSTICAL GLARE AND SURFACE DIFFUSIVITY INDEX. Concert music sounds better to a listener when the early sound is not glary and the late reverberant sound seems to arrive from many directions, from the sides, from the overhead, as well as from the front. Many of the best concert halls, most of which were built in the 19th century, have coffers, beams or curved surfaces on the ceiling, and columns, niches, irregular boxes, and statues on the upper side walls. The surfaces of the lower sidewalls often have fine-scale ornamentation. These irregularities and ornamentation diffuse the sound with the early reflections and give the music a mellow, non-glary tone. Diffusion must be thought of in relation to two different venues - those portions of the hall associated with the early reflections and those portions associated with the reverberant sound.

7) DIFFUSION OF EARLY SOUND. If one listens to music in a rectangular hall with flat, smooth sidewalls, the sound takes on brittle, hard or harsh sound, analogous to optical glare. For example in the New York Philharmonic Hall, because of the early lateral reflection from smooth plaster sidewalls, there was the sensation that upper tones from the violins contributed most to the glare. To reduce the acoustic glare related to the string tones that are caused by flat sidewalls or flat suspended panels, irregularities of the order 2.5-5 cm deep should be embossed into the reflecting surfaces. A further advantage of the diffusion is that the wall then distributes the early reflections from all instruments across a wide area of the sidewall, rather than from a different point for each instrument. The image shows two benefits of diffusion: the sound is coming from a wide area of the sidewall and EDT is more uniform for all the instruments.

8) OVERAL SDI OF THE HALL. For the Vienna Musikvereinsaal they determined an overall SDI of 0.96. The best halls have SDI of 05 to 0,9..

9) CLARITY is C80 in normal concert hall and is so highly correlated, with the reverberant time that it cannot be used as an additional way to estimate the acoustical quality of a concert hall. C_{80}(3) : in rehearsals in unoccupied space, conductors like the value to be from +1 to + 5 dB so that the details can be heard but when performing the same conductor would like the value to be -1 to -4 dB so that the performance is more reverberant.

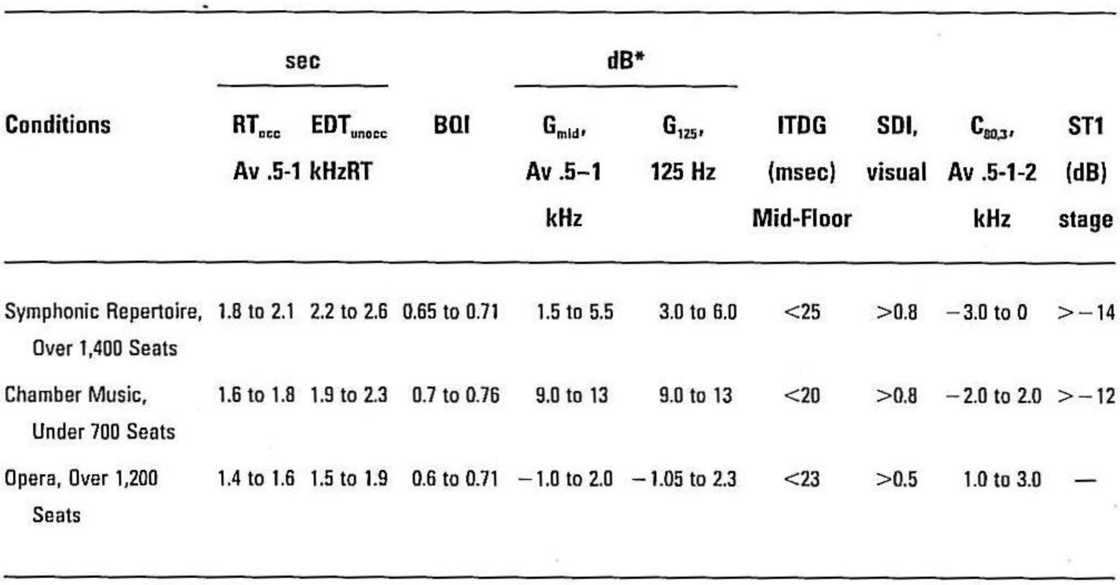
10) ST1 indicates the degree of stage support and it measures how well a player hears himself and other players near him. When a canopy is used to create a favorable ST1 on stage, its height should be between 7 and 13 m, adjusted according to the orchestra's preferences. ST 1 should equal approximately -12 to -15 dB. Generally speaking, halls with high ceiling and no canopy make it more difficult for an orchestra to play well as an ensemble. The conductor and musicians have trouble hearing each other and thus more closely watch the conductor's baton.

11) TEXTURE should be as in the graph.

12) BRILLIANCE should be obtained with dry air in occupied halls and no absorption material such as draperies and carpets in the space so that high frequencies over 2000 Hz are preserved because they give the brilliance to the music.

13) ECHO in a concert hall is generally caused by a reflection that is returned to the front part of the hall from a rear wall or a rear balcony face. The echo from the balcony enclosure is easily directed to the audience. An echo from the rear wall usually originates from the parts of wall below the first balcony. Tilting the wall either upwards or downwards can eliminate the echo. If upwards, adding some sound–absorbing material underneath the balcony would provide elimination of echo but it is wise to determine the amount of the absorbent material by actual tests after the hall is built, because of the small amount of material that is probably going to be needed. The worst possible echo can arise from a long rear wall that is circular with its focal point in the front of the hall or on the stage. The echo could be controlled by sloping the wall and setting any doors at an angle, or if not enough, absorbing material, or QRD diffusers, should be used on that wall.

Figure C- 31 Preffered values of acoustical parameters in concert halls, opera houses, and chamber music.



	sec			dB*					
Conditions	RT_{occ} Av .5-1	EDT_{unocc} kHzRT	BQI	G_{mid}, Av .5–1 kHz	G_{125}, 125 Hz	ITDG (msec) Mid-Floor	SDI, visual	$C_{80,3}$, Av .5-1-2 kHz	ST1 (dB) stage
Symphonic Repertoire, Over 1,400 Seats	1.8 to 2.1	2.2 to 2.6	0.65 to 0.71	1.5 to 5.5	3.0 to 6.0	<25	>0.8	−3.0 to 0	>−14
Chamber Music, Under 700 Seats	1.6 to 1.8	1.9 to 2.3	0.7 to 0.76	9.0 to 13	9.0 to 13	<20	>0.8	−2.0 to 2.0	>−12
Opera, Over 1,200 Seats	1.4 to 1.6	1.5 to 1.9	0.6 to 0.71	−1.0 to 2.0	−1.05 to 2.3	<23	>0.5	1.0 to 3.0	—

Figure C- 31 Preffered values of acoustical parameters in concert halls, opera houses, and chamber music.
(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

C 8.4 Worship spaces

See generally (Noxon;Web Page;*Auditorium Acoustics 101,102,103,104*; 2002).

Worship spaces are multiuse auditoriums and need to have both speech and music acoustics. Moreover, in churches there is a constant alternation of speech and music. Speech intelligibility is important in every worship space but different kinds of music have different acoustical requires. Late reflection can be absorbed and in this way eliminated but then much of the energy of reverberation is diminished. Late reverberation can also be splintered into numerous small reflections by being diffused. An early time gap exists between 1/16th and ¼ of a second following the direct sound. The acoustics of a gymnasium does not have this gap and a good auditorium will have it.

An amplified gospel choir requires a relatively low reverberation time and high definition while traditional church music requires a long reverberation time, often longer than 3 s. Also the size of the church is of great importance. Cathedrals are expected to have long reverberation in a spacious room with hard reflecting surfaces for the purpose of music and a singing congregation. In our times speech has been solved with sound amplification systems. In the past, attempts to make large churches good for speech relied on massive application of absorption but the result was a church dead for speech and music. With amplification, nowadays absorption is no more an option. In small and medium size churches speech can be intelligible without amplification and here the music is commonly amplified. Materials for worship spaces should usually be hard and reflecting, as for concert halls. Wood paneling absorbs low frequencies unless it is very thick or bonded. Brick stone and concrete are all appropriate materials for churches. Plaster is also good but should be relatively thick. Carpets should not be used, particularly near the organ and the choir. When sound absorbing treatment has to be resorted to for the control of reverberation or echo, it should not be placed on ceiling, which should instead be hard and reflecting. Upholstering reduces the sound energy. A rehearsal room should be at least 1 ½ stories high and extensively provided with absorption materials to reduce loudness, reverberation and flatten the echo between parallel walls. The region for the installation of absorption is between 50 cm to 180 cm above the flooring.

C 8.4.1 Acoustical demands for speech

In order to understand speech, it is important to hear the start, the sound and the ending of each syllable. Each syllable contains both loudness and tonal variations that add emphasis and can even change the meaning of the ultimate word. To understand speech, we must be able to hear and understand the rapid changing sonic variation within the syllables of speech. When people are speaking, they pronounce about 4 syllables per second and between syllables there is a short quiet moment. It is a model of the generation of a sequence of sounds each lasting 1/8th of second followed by 1/8th second silence. Anything that backfills the 1/8th second quiet time between syllables is noise and tends to mask or block out the understanding of the signal. Late reflections easily backfill those quiet 1/8th second period, causing separated speech syllables to seem slurred together.

Figure C- 32 echoes backfill the quiet between syllables

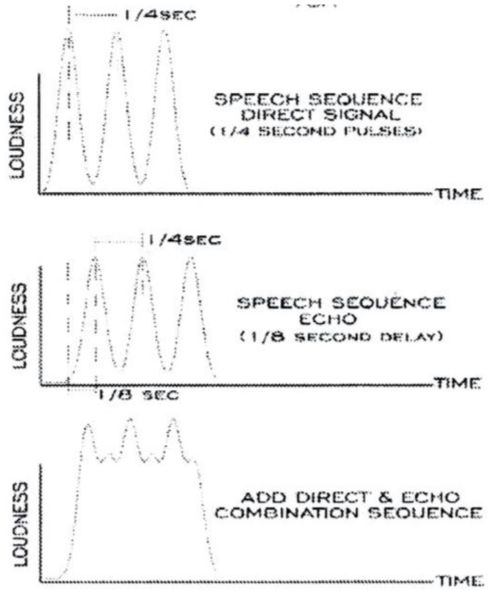


Figure C- 32 echoes backfill the quiet between syllables
(Noxon;Web Page;*Auditorium Acoustics 101,102,103,104*; 2002)

Late reflections are best to be converted into early reflections whenever possible because this helps to understand the direct sound.

A hall with sound characteristics good for speech has an early time gap in the sequence of ongoing reflection, an absence of late reflections

Figure C- 33 Late reflections are eliminated to improve intelligibility of speech in a hallI shows the direct sound and dense early reflections, after 14 ms of absence of the late reflections and after that the reverberation.

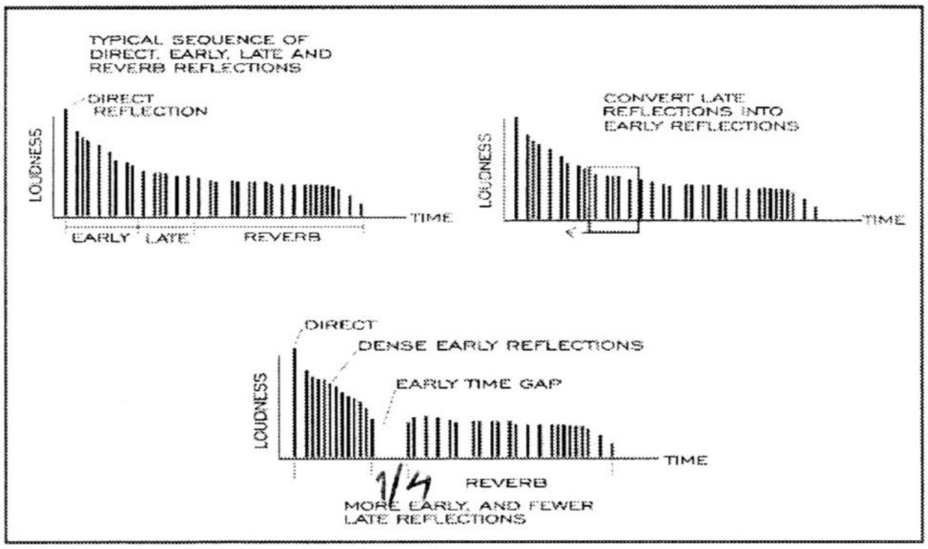


Figure C- 33 Late reflections are eliminated to improve intelligibility of speech in a hall (Noxon;Web Page;*Auditorium Acoustics 101,102,103,104*; 2002)

C 8.5 Sports facilities

Sports facilities are coliseums and sports activity arenas and stadiums that come into consideration with respect to their acoustics when they are usable for large musical events, orchestral concerts, plays and other cultural activities.

Sometimes curtains are used to divide a portion of the seating places. These large facilities have seating capacity of well over 5000 people, with an average of 25000 people. The basic problem in these buildings is that the surfaces are too far from the listener to provide useful reinforcement by reflected sound energy. Instead, reflections from boundaries are heard as echoes. The basic concept for these boundaries is to make them absorbing surfaces. Acoustic materials in the speech range of 200 Hz to 4000 Hz must have high absorption coefficient. Concrete is usually treated with thick absorbing foam boards that are left in place on the underside of the concrete. Steel surfaces on ceilings may have perforated absorbing sandwiches added. Upholstered seats are most suitable, or sometimes perforated seat bottoms that have sound absorbing material within the seat, which can be useful when the occupancy is low. These spaces, if untreated, have a reverberation of approximately 10 s and if treated 4 or 5 s, but this too is unacceptable. The important goal is to treat potential echo-producing surfaces and not to aim for a particular reverberation time. A big reason for massively using absorption is crowd noise. In large, untreated sports spaces, crowd noise can build up to the point where even massive, high level sound systems cannot communicate. With treatment, crowd noise during the exciting parts of events can usually be held in the range of 95 dB and sound systems can be designed to override such levels without causing hearing damages. For concert events stage enclosures or concert shells are used. The sound is always amplified with an electronic sound system, which has to address the problems of adequate levels, proper coordination in time with sound from the live source and uniformity of coverage.

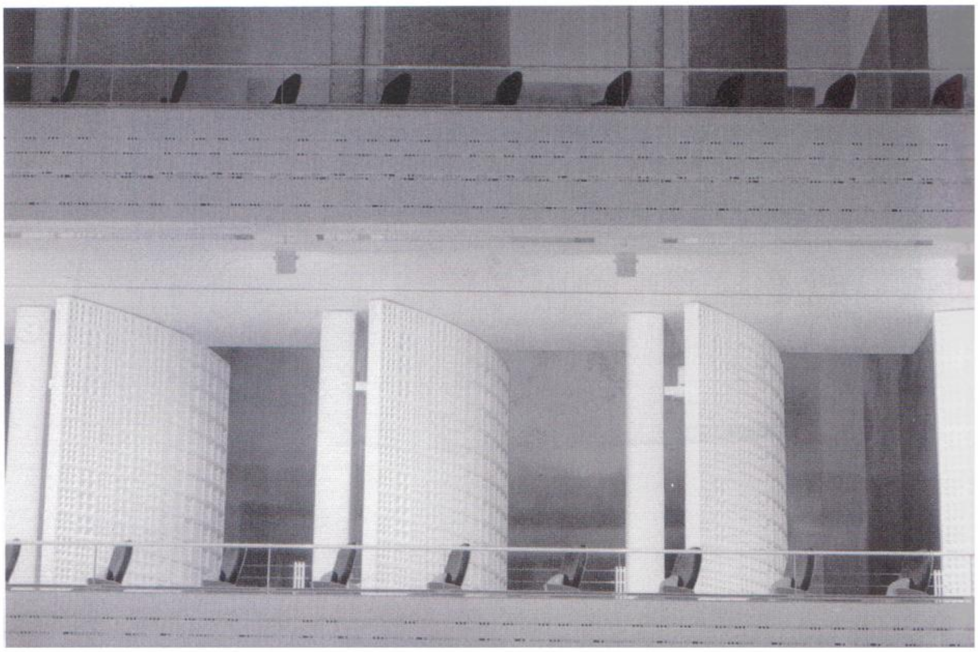
SECTION C 9 Multipurpose spaces

C 9.1 Multipurpose spaces_ adjustable or variable type of acoustics

A real need persists, however, for halls that can straddle a range of musical styles - halls with variable acoustics. Some attempts at such a design are halls that make use of devices to reduce reverberation time, such as retractable curtains, and devices that increase reverberation times, such as doors that permit the addition of large reverberant chambers. A few major halls are experimenting or have experimented with electronic augmentation- an art and craft that is slowly gaining in acceptance - but this effort still applies mostly to halls that need to correct for basic acoustical differences.

The question is addressed in two ways. The first way is to obtain different reverberations by building a bigger number of halls that are totally specialized for a specific purpose. A contemporary example of that principle is the Palau de les artes in Valencia designed by architect Santiago Calatrava. The other way of providing for variable acoustics is the use of additional chambers for reverberation, moving curtains and different partitions. An example of this kind of approach is the building in Lucerne by the architect Jean Nouvel. Both approaches demand a rather unsparing budget to get to the wanted effect of variable acoustics.

Figure C- 34 Switzerland, Lucerne, culture & congress centre concert hall, inside view
Figure C- 35 Switzerland, Lucerne, culture & congress centre concert hall, plan and section I
Figure C- 36 Switzerland, Lucerne, culture & congress centre concert hall, plan and section II



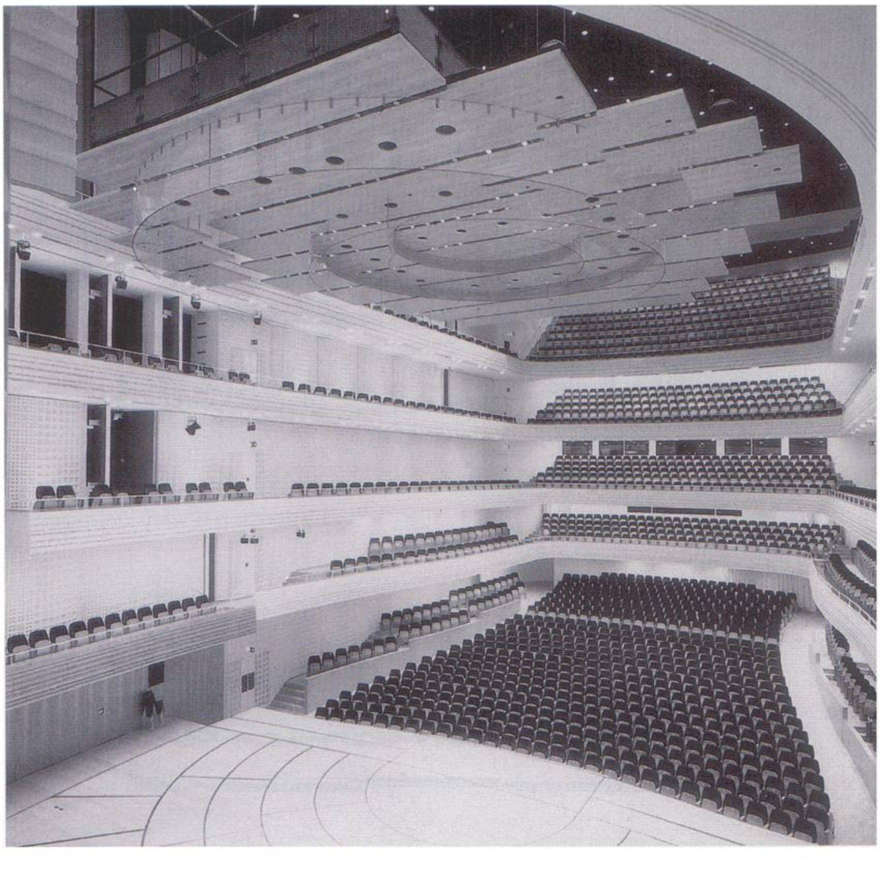


Figure C- 34 Switzerland, Lucerne, culture & congress centre concert hall, inside view (Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

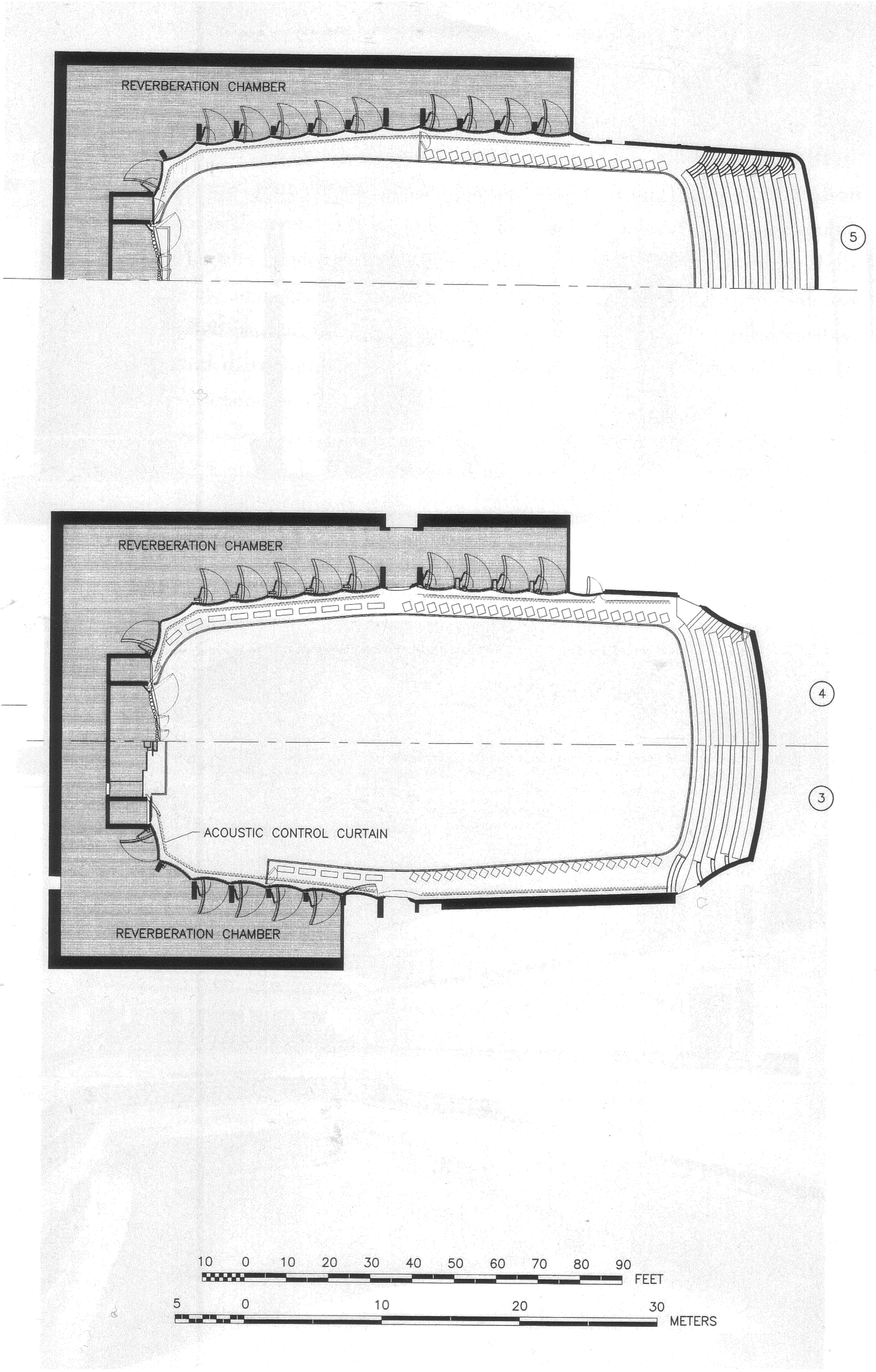
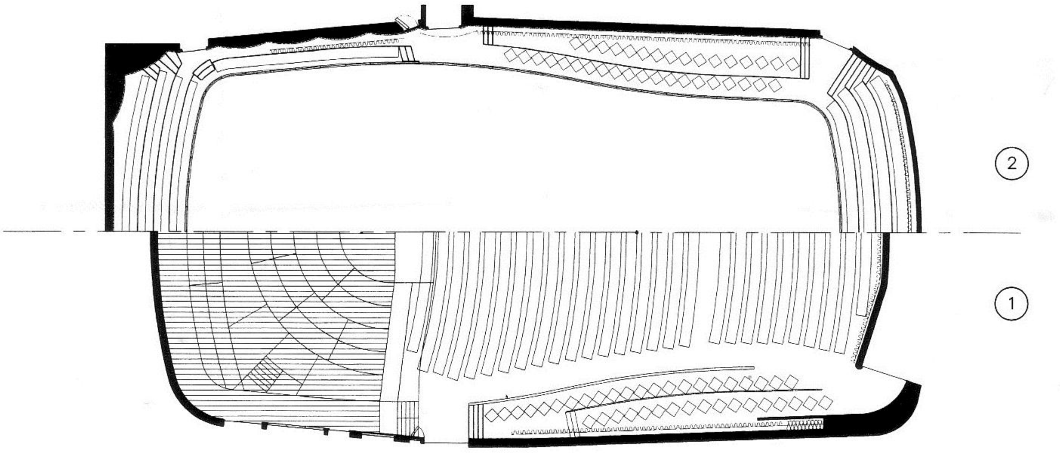


Figure C- 35 Switzerland, Lucerne, culture & congress centre concert hall, plan and section I

(Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)



SEATING CAPACITY 1892

①	778
②	352
③	214
④	234
⑤	314

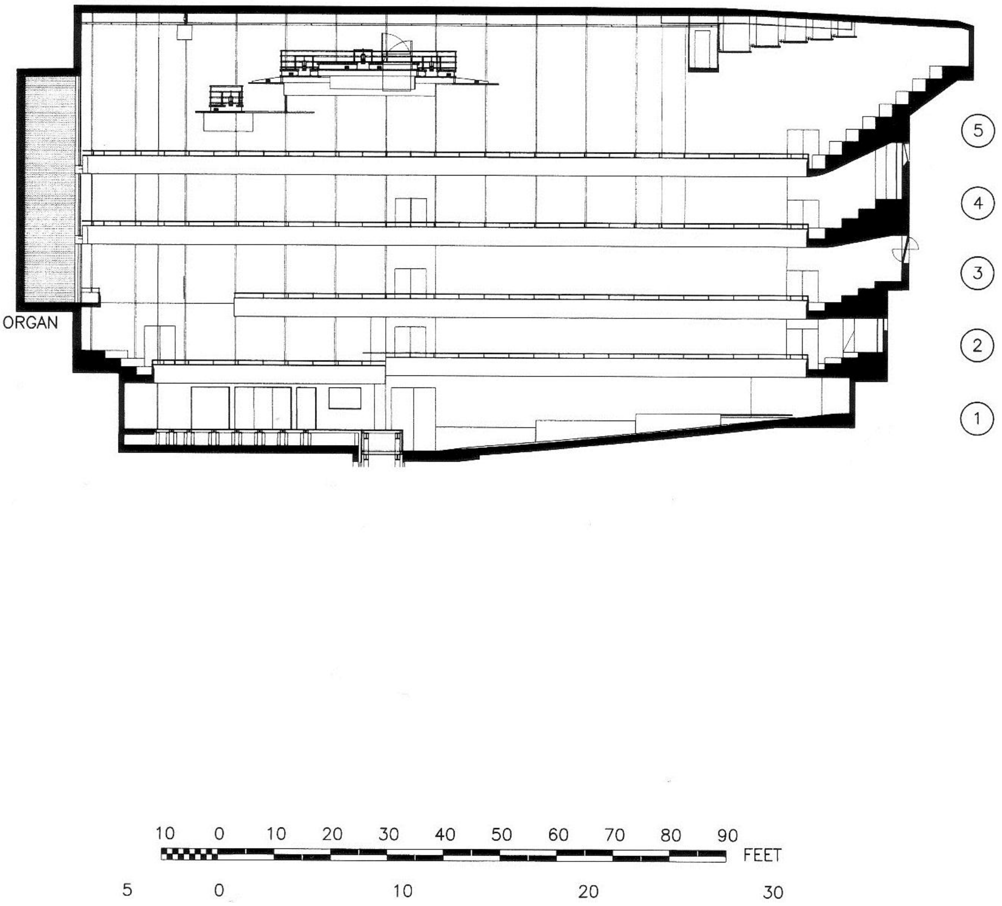


Figure C- 36 Switzerland, Lucerne, culture & congress centre concert hall, plan and section II (Baranek;Book;*Concert Halls and Opera Houses: Music, Acoustics, and Architecture*; 2004.)

Designing a hall with variable acoustics is the most complex acoustical task. In building this kind of structure the economic inputs and the effects that are gained with the construction of such a structure have to be balanced. Effects can include such things as acoustics for sound connoisseurs, endorsement of the status of the city in which the hall is situated or even region or country, or making breakthroughs in technology. In each case such a project has to succeed because otherwise the economic inputs aimed at the goals mentioned will simply be wasted. An important element is the money that has to be justified by the production of excellent acoustics. In designing variable acoustics in halls, acoustic consultants are of major importance. Furthermore, acoustical modeling in computer program and modeling the real hall in a scale of 1:10 or 1:20 is necessary. Designing variable acoustics is the most expensive way of obtaining high acoustic quality, and should be carefully weighed in comparison to the possibility of building an additional hall for different functions that will have substantially different sound characteristics. The most common solution is to build a large hall for pop concerts and big orchestras and large number of listeners with, beside them, little halls built for chamber types of performance. The best-known examples for adjustable acoustics are the Meyerson Center Hall in Dallas, Texas, the Symphony Hall in Birmingham, England, and the Culture and Congress Center Concert Hall in Lucerne, Switzerland. In all these cases, the main hall is essentially shoebox shaped, and surrounding the main hall there are concrete chambers with large cubic volumes that can be opened by heavy motorized doors. The good architectural practice used in numerous high quality halls is of the following kind. The main hall is essentially shoebox shaped. Surrounding the main hall, at different levels in each, are a number of concrete chambers with large cubic volumes that can be opened or closed by heavy motorized doors. Sabines reverberation formula says that with an increase in volume, the reverberation time is increased in direct proportion. In many halls that has not been achieved. In some halls the reverberation time is augmented just a few percentage points, and in some the increase is especially noticeable in the lower three frequencies 125, 250, 500. The reason is that it is difficult for higher frequencies to enter and exit the opening because they are short. But this can be solved by bringing a relatively large area of sound absorbing drapes to the audience chamber to reduce reverberation. Halls with short reverberation times are suitable for the performance of Baroque music. Such chambers are judged by musicians as desirable. But this addition is very costly and it is worth investigating how often reverberation will be varied in practice; a less costly hall may be a better choice.

The most complete data available are for the Concert Hall in Lucerne. There are three independently variable features in this hall: 1. 6,000 m3 of added reverberation chamber accessed in whole or parts by heavy, moveable doors, 2.1200 m2 of retractable sound-absorbent curtains that cover part of the inside walls, 3. a large canopy variable in height from 10 to 15 meters. This amount of variability provides the performers with a wide range of acoustic conditions: a) mid frequency, with reverberation time from 1.5 to 2.15 s, b) low-frequency reverberation times from 2 to 3 s, and c) canopy height suitable for large orchestras, 15 m, or for chamber groups, 10 m. The conductor has all these choices available, which can be at his will during a musical event. The hall is shoebox shaped and has an initial-time-delay gap of 23 ms, which combine to give it a high rating. CLARITY is somewhat special in various acoustics because for example the hall in Lucerne has extra reverberant chambers that create higher reverberation times at lower frequencies with full occupancy. The longer reverberation at frequencies lower than 500 Hz adds a new character to the music, not related to clarity.

C 9.2 Multipurpose halls_ neither adjustable nor variable

Multipurpose concert halls are the halls most discussed among acousticians; the reality is that most halls must accommodate nearly every sort of activity, including concerts. How well the multipurpose function is satisfied depends on 1 design concept, 2 budget, 3 auditorium placing. A design decision is whether there will be stage house or not, the auditorium being derived after this and so dependent. With the stage house there has to be a full orchestra enclosure and it is necessary to prevent loss of sound energy through wings and loft. Without a stage house, the design is more closely related to a concert hall but still appears as a traditional proscenium auditorium. There is then no difference between stage and auditorium volume. On stage orchestra enclosures should be provided, to provide communication, blend, ensemble and balance. The entire stage space may stay part of the auditorium volume. The orchestra enclosure elements can be designed to function as masks and borders for many non-concert uses. An acoustic environment that is ideal for one type of activity can be unsatisfactory for another - drama versus music, for example, and a good multipurpose auditorium design accommodates these differences by incorporating acoustic adjustability. Forms of adjustability are as follows. 1 Orchestra enclosures serve in multipurpose auditorium for converting the sending end of a basically theatrical stage into an efficient sending end for concert hall use. Enclosures widely used are lightweight modular devices that have poorer reflection in low frequencies and need lots of backstage space for storage. 2 Change of reverberation is usually achieved through a large area of tracked sound-absorbing curtains installed along the boundaries. When they are retracted into stage pockets, maximum reverberation is achieved and when they are extended reverberation is reduced to optimize speech intelligibility and to reduce loudness. Goals of movable stage enclosures are to: 1 prevent the loss of sound backstage with heavy and tight components 2 transfer and distribute the full range sound to the audience, accomplished with high opening towards the audience. It is very important to accomplish the reflection of low frequencies in the upper part of the enclosure because the lower part is lost across the audience area. So, it is important that the ceiling of the enclosure should not be of the lightest and leakiest components. 3 accomplish good balance. This means reinforcement of string section and deemphasizing drums and brasses because they are reinforced by upper surface and rear corners of the enclosure. 4 provide good on stage communication means feedback reflections. The requirement can be in conflict with the high ceiling criterion. To solve this problem the concept of a suspended panel array sub-ceiling should be used. This is a double enclosure effect and has lots of advantages. A large outer volume is provided for thereverberance; the movable inner element can be used to accommodate any type of performance. If amplified sound is used then the shape of the room is not important, but room boundary reflectivity is a dominant consideration. This is the principal mainly used in cinemas. And lots of absorption material is needed to achieve intelligibility

In generally if it is economically possible, a city should have a separate hall for each major purpose: symphonic concerts, chamber music, opera and ballet, and conferences. Otherwise, a multipurpose hall is necessary. Multipurpose halls are built when public investors are building an object that has to fulfill the need for a hall with numerous functions. The most common scenario after building multipurpose halls is the next phase, a future investment in which a hall that is going to have dominant purpose will be constructed. Of course, there are other reasons for the building of multipurpose halls, such as for example: the desire to attain the newest technological aims, insufficient land, on which only the construction of a multipurpose hall is possible. From evident reasons it is obvious that sometimes the clients are not in a position to pay such a high cost of a multipurpose hall. In that case the project is paradoxical, because investors do not have a substantial budget and the construction of a multipurpose hall costs more than investors would pay to build a hall with a dominating function. Building a multipurpose hall demands professional acoustical knowledge; such projects are specific; they should be led by acoustic consultants and real models should be made. In reality, multifunctional projects are halls with bad acoustics because there has been insufficient contribution by acoustical consultants. So, the result of the paradox in which the client does not have enough money for constructing several halls with several dominant functions and so opts to construct a hall with multifunctional acoustics is that the acoustics will be insufficient and bad. We should be aware of this practice and spare no pains to avoid the paradox and to find better a solution.

Approach to the design of a multipurpose hall when no adjustable type of acoustics is designed: the hall is built with a fly (scenery) tower. A demountable orchestra enclosure (shell) is provided for concerts, which, when in place, will result in a reverberation time that is on the lower edge of the recommended values say, 1.7 s. Each of the other acoustical factors should be as near to those recommended. These are: the strength of the sound, which depends on keeping the audience size as small as possible; the binaural quality index (BQI), which depends on early lateral reflections and results in a sense of spaciousness, and a sufficiently low ITDQ, which is responsible for the intimacy; and finally, adequate irregularities on the ceiling and side walls. For opera use, the fly tower should have, with the shell stowed, a reverberation time of 1.4 to 1.6 s. The highest rated opera house in the world, the Buenos Aires Teatro Colon, has an RT $_{\text{OCCUP}}$ equal to 1.6 s. For Italian opera alone 1.4 s is best. For speech events, large areas of sound draperies or banners that are otherwise concealed in pockets in the sidewalls or the ceiling would be exposed. If the total area is large enough, the RT can be reduced by 0.2 to 0.3 s. For amplified speech using column-type (directional) loudspeakers an RT of less than 1.5 s is a satisfactory environment for lectures. With loudspeakers, in smaller halls, the reverberation should be 1.2 s or less.

It is also possible, to achieve variable acoustics, to resort to the domain of the sound amplifier NPR MCR System, in which MCR is Multiple-Channel Amplification of Reverberation. This system at Theatre Claude Debussy, Cannes enables remote control of reverberation in 10 steps between 1.45 and 2, 0 s and a sound level of 110 dB. This is a system of amplifiers hanging in a false ceiling, behind false side walls and in the ceiling below the balcony; these look like standard reflectors but are in fact loudspeakers. System Ambiophonie is incorporated in Teatro alla Scala in Milan, Italy.

The system at Theatre Claude Debussy, Cannes provides remote control of reverberation in 10 steps between 1.45 and 2, 0 s and sound level 110 dB. This is a system of amplifiers suspended in a false ceiling, behind false side walls and in a ceiling below the balcony that looks like standard reflectors but in fact consists of loudspeakers. System Ambiophonie is built into the Teatro alla Scala in Milan, Italy

Besides the shape problem, and no single perfect shape can ever be defined, it is also often a problem to get a definite programme for the space. This means that often investors are not sure what they want and what to expect so the program or demands of the space design evolves with the project. As stated before, the more undefined the elements in a sound are, the harder it is to establish a definite design methodology. Not knowing the function of the space in detail makes the process of designing the space more creative, more demanding and in the end more difficult. This is also one more aspect that relativises any hard and fast methodology for getting excellent sound quality.

SECTION C 10 Summary of Recent Studies

C 10.1 Summary of Recent Studies

See generally (Cavanaugh & Wilkes;Book;*Architectural Acoustics: Principles and Practice*; 1999).

1) People seem to prefer different reverberation times for different types of music and other acoustical activities _Sabine 1927, Cremer and Muller 1982, Ando 1985

2) The early portion of the reverberant decay is important in people’s perception of reverberation_Schroeder 1974, Jordan 1974

3) People only notice the decay of the first 10 dB because after that a new sound signal arrives to listener. EDT is thusmore important than RT60

4) It is possible to provide sloped decays in rooms so that clarity may be provided by early reflections arriving shortly after the direct sound while a long reverberation tail provides a sense of fullness and reverberance_ Johnson 1990

5) Early sound shortly after the direct sound contributes to clarity and loudness of sound. Early sound is responsible for clarity and envelopment, and the later reverberation tail that should be lower in dB provides fullness without interfering with clarity. This is the way in which simultaneously to gain clarity and fullness. picture 238 aa

6) The reverberation time should increase somewhat in low frequencies to provide a sense of acoustical warmth_Baranek 1962

7) Reverberation time at 125 Hz should be 10 to 50% longer than in the mid frequencies. Loudness in low frequencies should also be greater than in the mid frequencies. Several reflections from the ceiling are needed to arrive shortly after the direct sound, within first 50 or 80 ms, especially in the rear portion of the room, to increase the overall level of the sound and to provide clarity_Veneklasen 1979, Thiele and Meyer 1977, Cremer and Muller 1982.

8) Sound arriving in first 20 to 50 ms increases loudness. After 70 and more ms an echo appears.

9) How loud a sound should be at specific time delays to reinforce the direct sound, while in a second stage it becomes a contribution to loss of clarity or intelligibility and in a third stage it contributes to forming an echo_many studies

10) Generally the sound that comes within 50 to 80 ms after the direct sound and is just somewhat lower than the direct sound contributes to loudness. The early sound that comes within first 40 ms will also contribute to intimacy. If the sound arrives from many directions than it is called reverberation and contributes to spaciousness. If it is possible to distinguish where it comes from, then it is echo. If reverberation has strong loudness at low frequency, it will increase the sense of warmth. If reverberation has strong loudness in higher frequencies, then it contributes to brilliance.

11) The arrival of the first reflection, initial time delay gap should follow the direct sound within 20 ms_Baranek 1962

12) This forms intimacy in the room. It indicates how close we are to the direct sound. Intimacy can be improved by reflecting surfaces close to listener, so that the surfaces are a new source of sound.

13) Reflections arriving from the sides, lateral reflections, within 80 ms after the arrival of the direct sound provide a sense of spaciousness, spatial impression, envelopment and increase the apparent width of the sound space._ Barron 1993, Marshall 1967, Johnson 1990

14) ASW apparent source width. It becomes plainly evident to anyone who takes a pair of stereo loudspeakers in their living room and begins to move them apart. Further, if to this loudspeaker few loudspeakers were added the spaciousness would increase because of more early lateral reflections. The spaciousness can be increased by raising the volume of the sound. If several additional loudspeakers are placed towards the rear wall and if reverberation is added people feel as if they are enveloped in sound field. This produces an effect similar to a binaural effect and people feel enveloped by the sound.

15) Musical sounds are preferred to arrive somewhat different to listeners right and to listeners left ear._Gottlob in Cramer and Muller 1982, schroeder 1974, Ando 1985, Barron and Marshall 1981 Preferably, musical sounds should arrive somewhat differently to the listener’s right and left ears

16) Interaural cross correlation is the usual measure of this quality and it contributes to envelopment or spaciousness.

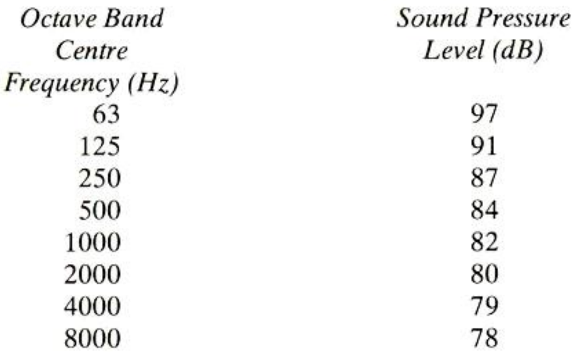
17) The sound level should be adequate at all seats in the house_Sabine 1927

18) Loudness is probably the most important acoustic quality in a room. The balance between soloist and orchestra is important. It is difficult to achieve the same level of loudness because of the different dynamics from pianissimo to fortissimo in the piece.

19) Preferred listening levels have been identified_Ando 1985.

20) That preferred overall level is in general 79 dB.

Figure C- 37 Maximum recommended Octave Band Sound Pressure Level (SPL)



Octave Band Centre Frequency (Hz)	*Sound Pressure Level (dB)*
63	97
125	91
250	87
500	84
1000	82
2000	80
4000	79
8000	78

Figure C- 37 Maximum recommended Octave Band Sound Pressure Level (SPL)

(Decimin Control Systems P. Ltd. ; Web Page;*Technical information*)

21) The timber and frequency response of sounds should be preserved_Sabine 1927, Bech_1995

22) Elective absorption of some frequencies should be avoided.

23) The sound field should be reasonably diffuse_Thiele and Meyer 1977, Beranek 1962, Cremer and Muller 1982, Chiang and Frick 1994

24) A stage enclosure should allow musicians to hear each other, provide support and ease of ensemble for musicians_Gade 1989

25) Reflections from an enclosure provide reflection for the musicians to hear each other, to achieve ensemble and play unison. Acoustical measures ST100 and ST200 evaluate the acoustics of stage enclosure.

26) The quality of sound differs within a room and among different rooms_ Hawkes and Douglas1971, Barron 1988, Cervone 1990

27) The difference between different seating locations in several large rooms is greater than the sound differences between two rooms.

28) Feelings and opinions about sound quality will differ according to the given space and to who is perceiving.._Wilkens in Cramer and Muller 1982, Barron 1988, Cervone 1990, Chiang 1994

29) Loudness, clarity, timber in 90% of examined German concert halls explored by Wilkens.Reverberation, intimacy and envelope found as major for impression by Barron. Clarity, intimacy and envelope were dominant in Cervone.

30) Interaction between many of sound qualities contributes to overall acoustical impression._Barron 1988, Cervone1990, Chiang 1994, Bluauert and Lindemann 1986, Barron and Marshall 1981, Ando 1985, Schroeder 1974.

31) Envelope increases as loudness and reverberance increase. The combined effect of multiple variables makes isolating the particular effect of any one variable more difficult to determine. Spaciousness has been determined. Ando proposed four factors determining subjective preference of sound field: listening level, initial time delay gap, reverberation time, interaural measurement. Schroeder’s factors are: distinctness, reverberation time, the interaural cross correlation.

32) Methods to assess qualities of sound were developed through these years of pioneering work on acoustics: Evaluation of live performance, interview studies, listening to recorded music in a hall, analysis of sound in the laboratory by evaluation of recorded and simulated sound field, or by evaluating acoustic test signals.

SECTION C 11 Conclusion to Part C

Part C is the most important and largest part of this dissertation. It reveals the contemporary methods themselves.

The revelation of methods begins with the historical observation of periods and methods used. This is followed by a description of the actual standard procedures of contemporary methods. It is shown that historical methods have been upgraded. They have not been demolished for new methods to be established. Contemporary methods are updated and modernized versions of those of history.

Also, the goal of presenting contemporary methods was to reveal the possibility of standardising methods. Methods for typical spaces were shown; standard contemporary calculations were shown, as well as other major elements that contribute to the method. These elements include the things to be avoided, the major items of concern, the design procedures.

The standardization of methods is possible in one part of the process. Standardization is only possible in calculating or deciding on initial conditions. However, the process between architect and acoustician cannot be standardized. The process of evaluation between architect and acoustician cannot be limited or predicted because what is involved is the will to decide when to stop with modelling. In the evaluation process the major role is played by the architect who supervises the idea of the project. Accordingly there is no fear that architect might be excluded from the project just because the project needs precise acoustical calculations.

The knowledge of the particular process of evaluation between acoustician and architect logically led to the next part of dissertation: in Part D, real projects were shown and evaluated.

In this part it is evident that defined limits can assist in defining a method for high quality sound calculation and design. For instance, from the newest results in a preferred sound level it is evident that people tend to prefer a sound of 76 dB. This figure is of major help for defining some parameters that were indefinite, such as reflection. Here lies a limitation in defining how many reflections are necessary in order to get high quality sound because in Part B above it was stated that the more reflections, the more sound. And now that 76 dB has been defined as the preferred sound we can finally know how many reflections we need to get to that preferred level.

In this Part C it was important to find out some further limits that could help in standardizing a method for quality sound. Seven criteria that are used in the contemporary method are of major importance, and further unwanted criteria that should be avoided, for this will help to standardize the methodology. The steps needed to be taken to construct such a methodology are: finding the shape and after that the finalisation in the calculations and decisions about materials. It should be here one more time pointed out that the more limits or definitions there are, the closer we are to a standard method. But, there are problems that still are not limited and defined that relativise the method for achieving a high quality sound. These indefinite values are: the problem that human beings feel the sound and every person feels it differently, more or less intensely. Also, listeners hear the sound differently from acousticians. Whose sound image is then correct? A further question is what type of sound is imagined as high quality, or preferable? Is it indoor or outdoor sound? If indoor, does it mean the sound listened to from a distance of 1 or 10 m? Our contemporary image of sound is also a question. Is our image correct when knowing that we are living in a period in which different periods' sound images are tolerated? Does the image of sound evolve through time? Could and should the sound image be cleared of its temporal and social context? Calculating results in computer programs is also a creative thing because it needs an acoustician to know how to estimate the criteria so as to obtain a result acceptable to the architect. The questions and problems listed in fact cast doubt upon or break down the concept of any standardized methodology for quality sound.

PART D Acoustic study of halls for music

PALAU DE LES ARTS, VALENCIA containing six different halls and

ARENA, Zagreb for 15 000 auditors

SECTION D 1 Overview_ Palau de les Arts, Valencia

See generally ("Palau de les Arts, Valencia," 2008), ("Palau de les Arts Reina Sofía opera house. Valencia," 2008.), ("The Building," 2009).

The main hall of the Palau de les Arts Reina Sofia Opera House, a complex venue in the city of Valencia, was opened to the public on October 8th, 2004. Although in first drawings designed as an opera theatre it later became and was designed in concert mode with an orchestra shell in the stage.

The architect Santiago Calatrava designed it as an open space music hall, but it was in the project process reformulated into a ceilinged space because of problems of the loud noise from outside that was difficult to reduce due to heavy traffic in thesurroundings.

The building designed by the Valencian architect Calatrava, contains 4 halls for music and theatre performances together with 2 main rehearsal rooms.

The main building is designed with the dual intention of acting as a multi-hall auditorium and creating an urban landmark of a certain monumentality that at the same time plays a role as a dynamic feature of the urban area, consolidating the setting and becoming a symbol of Valencia. This work should be seen as a vast sculpture with great symbolic content: its nautical forms suggest its closeness to the sea and its setting in the former bed of the Turia River. The overall form of the building is lenticular, developing under a huge metal roof of „plume“ held up by two supports, one at its western end and the other intermediate, with the eastern end of the roof totally projecting. The material par excellence is white concrete, as this forms part of the great structural supports of the building, while the „trencadis“, which is broken tile effect is the second most widely used material covering the spectacular „shells“ of the Palau. The Palau de les Arts Reina Sofia has four different halls: the main hall, the master class room, the amphitheatre and the chamber theatre. The building also has facilities for teaching and other activities closely connected with the artistic and cultural fields.

A number of auxiliary aspects involved in staging productions have been taken into consideration as a result of the main opera house activity. This entails the installation of assembly and repair workshops: carpentry, mechanics, electricity, wardrobe, footwear, etc. There are also storage areas for housing scenery, flats, stage properties and wardrobes, as well as storage for the seats of companies using the facilities. The use of diverse auditoriums requires the presence of rehearsal rooms of different types, such as joint rehearsal rooms - song, dance, orchestra and other individual areas - wind, violins, cellos, basses... These areas will be connected to the dressing rooms, rest areas and cafeteria. In the private area, the Palau de les Arts Reina Sofia has offices for general administration, artistic and technical direction, large rehearsal rooms for orchestra, choir, dancers and soloists, press rooms, stage production room, VIP dressing rooms, individual dressing rooms for soloists and dressing rooms for extras, choir and orchestra, as well as catering facilities, workshops, tailors, carpentry and storage located on level -12,00.

The roof is the grandest part of the complex. Apart from its painstaking structural and geometrical design, it is extremely expressive in its intention of conveying to the outside world the artistic nature of the activities taking place inside. The roof of the plume is the most structurally spectacular detail, 230 m in length and 70 m in height, while the two shells which embrace the building on the outside are made of laminated steel with an approximate weight of 3000 tons and feature delicate „trencadi“ ceramic work on the outside. The maximum enveloping dimensions of the building, taking into account the curved shapes which give it its form, are 163 m in length by 87 m wide.

It is a building that incorporates an acoustic study developed over a long period of time.

GARCIA-BBM S.L. began the collaboration with the architect as early as 1996 with the first initial drawings and has produced more than 200 reports on the acoustic aspects of the project.

The project began in 1996. The Ciudad de les Arts Cultural Centre was built on the existing base of a telecommunication tower and the Main Hall was opened in October 2004.

GARCIA-BBM began with geometrical studies which gave way to computer simulation techniques to study the acoustic response of the hall, with REFLEXSON software.

As acoustic consultants for the Palau de les Arts in Valencia GARCIA-BBM S.L was responsible for the acoustic design of the Building and in particular of the four acoustically critical Halls:

1) The Opera House or Main Hall
2) The Auditorium
3) The Chamber Music Hall
4) The Experimental Theatre
5) as well as the Rehearsal Rooms for Orchestra, Choir and Ballet.

GARCIA-BBM worked with the Architect and his Studio on all aspects related to the acoustics of these halls to ensure the adequate acoustic conditions for their multipurpose uses. These included:

1) The geometry of the halls
2) The acoustic insulations of the building elements
3) The interior finishes
4) The control of noise and vibration emissions of mechanical installations.

The following text outlines the geometric characteristics of the halls, their volumes, their different uses and the criteria for each use. The acoustic results achieved once construction was completed are briefly summarized.

Figure D 1 Longitudinal section of the Palau de les Arts

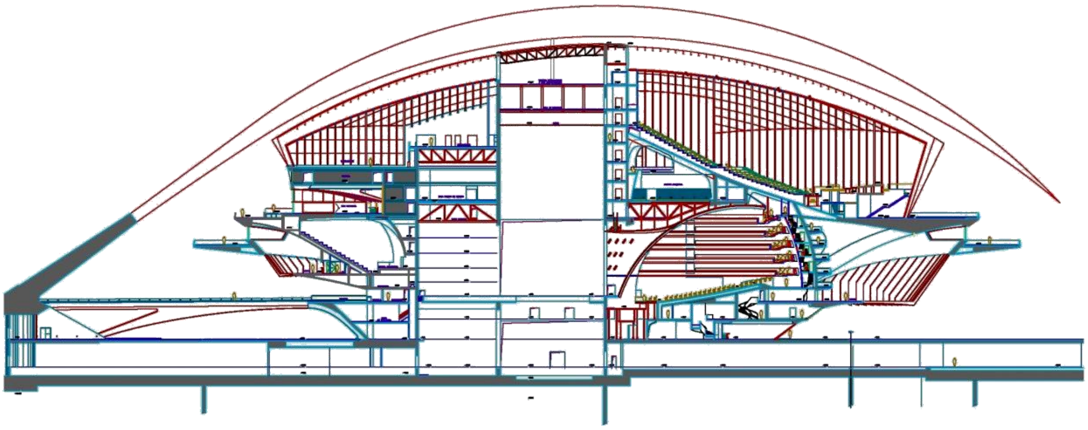


Figure D 1 Longitudinal section of the Palau de les Arts
("Palau de les Arts, Valencia," 2008)

D 1.1 Palau de les Arts _main hall. Example of space for symphony for 1700 auditors

This Hall is the most representative hall of the building. The size both of the stage and of the orchestra pit make it particularly suitable for large operas, although it can be used for concerts of symphonic music, and ballet with and without artificial sound reinforcement.

The MAIN HALL, seating 1700, is the core around which the building generates both its formal and structural aspects. It is located within the structural support of the building created by curved surfaces and interior boxes of white concrete forming an epidermis with intense visual power. The meeting foyer lies around the main hall providing a perimeter route to access the rooms beside the hall; spiral ramp staircases mean that there are exits from the hall at different heights. The interior of the stalls is understood as a single volume where the whole audience will be seated so as to have an overall view of the hall. Its longitudinal section is generated through the audience sight lines towards the stage. The opera boxes so characteristic of this type of building are set out at four heights alongside on the vertical faces.

The architect chose a classic horseshoe type of shape for the main hall, with four rows of balconies without the traditional closed boxes. That shape presents some visibility problems on the sides of the hall, particularly close to the stage, but sound presence in those places is helped by short reflections from the ceiling.

The double shape of the ceiling, convex at front and slightly concave at the rear, distributes sound uniformly to the different parts of the hall.

The most challenging part of the project was the study of a movable part of the ceiling which includes 18 beams made of steel and glass that could move down onto the stage creating a glass curtain in front of the proper fire curtain and that will move up to the ceiling again to provide a great lighting surface.

Unfortunately this movable curtain could not be operated during the opening night and remained fixed in the ceiling.

The second singular feature of this hall is the material used in its internal surfaces, broken ceramic pieces, called “trencadis” for the walls, steel and metacrylate plates for the ceiling, plasterboard for the front of the balconies and wood directly fixed to the concrete for the floor. Seats are finished in blue leather with some perforation in the underneath parts, which offer less absorption than cloth-finished seats and therefore the difference in acoustic terms between the empty and occupied hall is more significant.

GARCIA-BBM designed the telescopic orchestra shell, which incorporates 19 mm thick wood panels to minimise low frequency absorption. The shell is built in modular pieces that allow different configurations: large orchestra and chorus, large and small orchestras etc.

With the hall empty the reverberation time is 2 seconds at all frequencies, with excellent values for clarity for both speech and music.

The success of the opening night confirmed the expectations of a hall with excellent acoustics for an opera hall in concert mode with 1.8 second reverberation time at low frequencies and 1.6 at mid frequencies.

Figure D 2 Palau de les Arts_ Main Hall plan view and Figure D 3 Palau de les Arts _Longitudinal section of the Main Hall

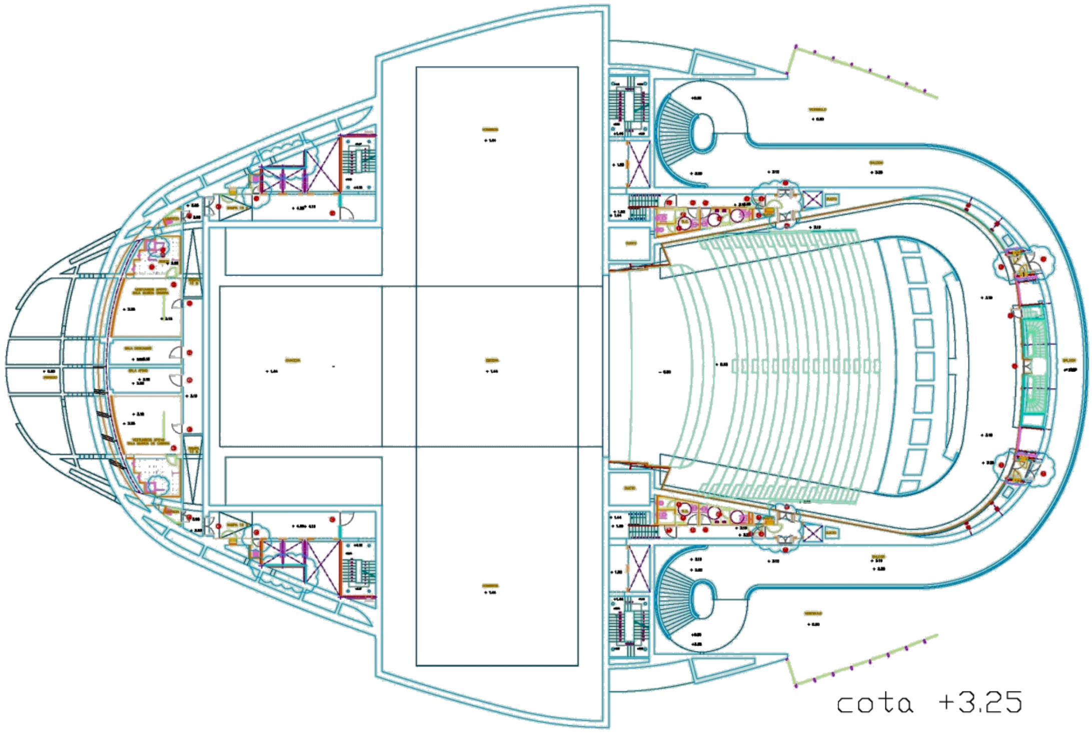


Figure D 4 Palau de les Arts_ Main Hall plan view
("Palau de les Arts, Valencia," 2008)

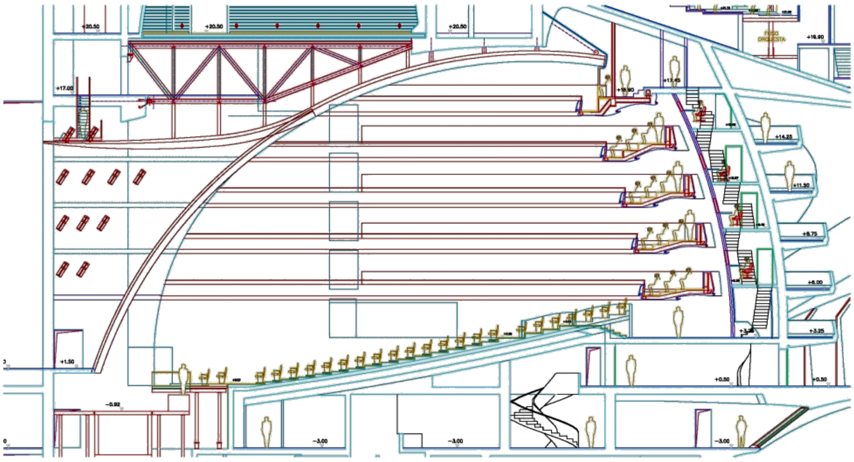


Figure D 5 Palau de les Arts _Longitudinal section of the Main Hall ("Palau de les Arts, Valencia," 2008)

D 1.1.1 Basic characteristics of the Hall

Tables 1.1-I to 1.1-VI show the dimensions, surface areas and volume of the Hall, as well as the seating capacity for both main uses of the Hall. This is all shown through Figure D 6 Table 1.1- I Palau de les Arts_Main hall dimensions,Figure D 7 Table 1.1- II Palau de les Arts_Main hall stage dimensions,Figure D 8 Table 1.1- III Palau de les Arts_Main hall stage surfaces,Figure D 9 Table 1.1- IV Palau de les Arts_Main hall orchestra pit dimensions,Figure D 10 Table 1.1- V Palau de les Arts_Main hall acoustic shall Figure D 11 Table 1.1- VI Palau de les Arts_Main hall seating area

TABLE 1.1-I	
HALL	
DIMENSIONS	
Apron	2,7 m
Proscenium	width 19,3 m depth 2 m Height 12,8 m
Hall	minimum width 19,3 m maximum width 20,8 m maximum width with boxes 29,2 m length 36,5 m average height 14,5 m
Distance between rows	0,95 m
Distance between the stage opening and the furthest auditor	36,8 m
SURFACE AREA	
Apron	52 m2
Floor area	735 m2
VOLUME	
Total	13000 m3

Figure D 6 Table 1.1- I Palau de les Arts_Main hall dimensions

("Palau de les Arts, Valencia," 2008)

TABLE 1.1-II	
STAGE ENCLOSURE	
DIMENSIONS	
Stage opening:	width 17 m height 12.8 m
Stage:	width 26 m depth 20.4 m height 33.7 m
Louvre Wall: (Chácena)	width 26 m depth 15.8 m height 14.5 m
Left wing	width 20.4 m depth 16 m height 13 m
Right wing	width 20.4 m depth 16 m height 13 m
Stage Pit	width 26 m depth 20.4 m height 14 m
Lower louvre wall	width 26 m depth 15.8 m height 13 m
Lower left wing	width 20.4 m depth 16 m height 9 m
Lower right wing	width 20.4 m depth 16 m height 9 m

Figure D 7 Table 1.1- II Palau de les Arts_Main hall stage dimensions

("Palau de les Arts, Valencia," 2008)

TABLE 1.1-III	
STAGE ENCLOSURE	
SURFACES	
Stage:	530 m2
Louvre wall:	410 m2
Left wing:	326 m2
Right wing:	326 m2
TOTAL STAGE AREA:	1592 m2
Stage pit:	530 m2
Lower louvre wall:	410 m2
Lower left wing:	326 m2
Lower right wing:	326 m2
TOTAL BELOW STAGE AREA:	1592 m2
VOLUMES	
Stage:	17860 m3
Louvre wall:	5940 m3
Left wing:	4230 m3
Right wing:	4230 m3
TOTAL:	32260 m3
Stage pit:	7420 m3
Lower louvre wall:	5330 m3
Lower left wing:	2930 m3
Lower right wing:	2930 m3
TOTAL:	18610 m3

Figure D 8 Table 1.1- III Palau de les Arts_Main hall stage surfaces

("Palau de les Arts, Valencia," 2008)

TABLE 1.1-iV	
ORCHESTRA PIT	
DIMENSIONS	
Open Area:	18 m minimum width 20.3 maximum width 21.5 m maximum extended width 5.7 m length 7.4 m extended length
Covered and open area:	18 m minimum width 20.3 maximum width 21.5 m maximum extended width 7.8 m length 9.5 m extended length
Platform:	4 (1 for seats)
SURFACE AREA	
Minimum (Open Area)	110 m3
Minimum Covered Open Area	150 m3
Maximum (Open Area)	145 m3
Maximum Covered Open Area	180 m3

Figure D 9 Table 1.1- IV Palau de les Arts_Main hall orchestra pit dimensions

("Palau de les Arts, Valencia," 2008)

table 1.1-V	
ACOUSTIC SHELL	
Telescopic (Modular) Dimensions:	width 17 m depth 8.8 m height 12.8m
Surface Area:	150 m2
Volume:	1800 m3

Figure D 10 Table 1.1- V Palau de les Arts_Main hall acoustic shall

("Palau de les Arts, Valencia," 2008)

table 1.1-VI	
SEATING AREA	
Stalls:	842 Seats (62 in pit)
Boxes (+6.00):	253 seats
Boxes (+8.75):	244 seats
Boxes (+11.50):	207 seats
Boxes(+14.25):	197 seats
TOTAL:	1743 seats

Figure D 11 Table 1.1- VI Palau de les Arts_Main hall seating area

("Palau de les Arts, Valencia," 2008)

D 1.1.2 Uses and criteria

As mentioned above the Main Hall has been principally designed for all types of opera productions. However, the presence of an acoustic shell makes it possible for the Hall to be used for symphonic music although its volume limits this use. The Hall can also be used for ballet, classical and modern dance as well as concerts with amplified music.

TABLE 1.1-VII presents the acoustic criteria established at the beginning of the project and which still applies.Figure D 12 Table 1.1- VII Palau de les Arts_Main hall basic two purposes: opera and concert Figure D 12 Table 1.1- VII Palau de les Arts_Main hall basic two purposes: opera and concert, Figure D 13 Palau de les Arts_ Main hall as seen from the Stage.

TABLE 1.1-VII	
BASIC ACOUSTIC CRITERIA	
OPERA	
Reverberation Time (T60)	1.4 – 1.5 ss (occupiedl)
EDT:	The optimum adjust to T60 classic
C50:	Between -5 and +1
Total Level:	>=0
Speech Intelligibility:	>=90%
Background Noise:	NC-15
CONCERT	
Reverberation Time (T60):	1,7 - 1,8 ss (occupied)
EDT:	The optimum adjust to T60 classic
C80:	Between -2 and +2
Background Noise:	NC-15

Figure D 12 Table 1.1- VII Palau de les Arts_Main hall basic two purposes: opera and concert

("Palau de les Arts, Valencia," 2008)

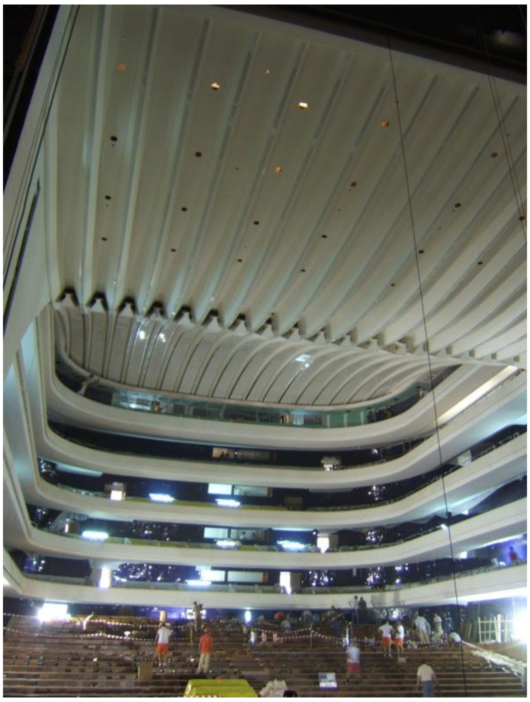


Figure D 13 Palau de les Arts_ Main hall as seen from the Stage.

("Palau de les Arts, Valencia," 2008)

D 1.1.3 Interior finishes

Table 1.1-VIII summarizes the interior finishes of the Main Hall. The seats are covered in leather and are the design of the architect Santiago Calatrava.Figure D 14 Table 1.1- VII Palau de les Arts_Main hall material application,Figure D 15 Palau de les Arts_Main hall as seen from a box

table 1.1-VIII Palau de les arts interior finishes of the main hall	
SURFACE	MATERIAL
CEILING AREA NEAR PROSCENIUM STAGE	Gypsum board >20 mm thick
CEILING AREA COVERED BY MOVING DOOR (CANCELA)	Gypsum board >20 mm thick
(CANCELA) MOVING DOOR LATERAL PARTS	Gypsum board 20 mm thick
(CANCELA) MOVING DOOR VISIBLE PARTS	Glass or methacrylate (16 Kg/m2)
LATERAL WALL (BETWEEN STAGE AND BOXES)	Dense wood 20 mm thick Gypsum board 20 mm thick Strips of wood 40 x 30 mm with a separation 15 mm sured to the inner surface
PARAPETS	Gypsum board >20 mm thick
CEILING BOXES	Gypsum board 20 mm thick
REAR WALLS BOXES	Thin painted concrete or gypsum board 30 mm thick, covered by pieces of broken ceramics (Trencadis)
ACOUSTIC SHELL (Concert mode)	Dense wood 20 mm thick
STAGE FLOOR	Wooden floor 40 mm on wood joists
FLOOR IN HALL	Thick wood and marble
ORCHESTRA PIT FLOOR	Wooden floor 40 mm on wood joists
ORCHESTRA PIT WALLS	Gypsum board 20 mm thick
ORCHESTRA PIT CEILING	Gypsum board 20 mm thick

Figure D 14 Table 1.1- VII Palau de les Arts_Main hall material application

("Palau de les Arts, Valencia," 2008)

Figure D 15 Palau de les Arts_Main hall as seen from a box

("Palau de les Arts, Valencia," 2008)

D 1.2 Palau de les Arts _the auditorium. Example of variable acoustics space, amplified for 1500 auditors

An AMPHITHEATRE with seating for 1500, its facilities include advanced sound, cinema and video systems for live performances and shows and for projecting cultural events on large screens, including the opera performance being put on in the main hall at the same time.

The Auditorium area was initially an open air venue for events which do not require low background noise levels or excellent acoustic conditions (for example for pop groups or amplified music). Later it was decided that the area should be enclosed and converted into a Hall for Symphonic Music. An orchestra pit was included in the Hall enabling it to be used for light operas such as zarzuelas and Baroque opera.

Due to it being situated in a cantilever system there are load limitations and this has made it necessary to study the use of light enclosures which offer a high level of acoustic Insulation. Moreover its position between level + 17 and level +35 makes access difficult for heavy or large stage sets.

However the Auditorium has a volume which permits optimum acoustic conditions for concerts of symphonic music and in this respect it is better than the main Hall, which, being designed for operas, has much less volume.

Figure D 16 Palau de les Arts_Plan of the Auditorium is an example of variable acoustics

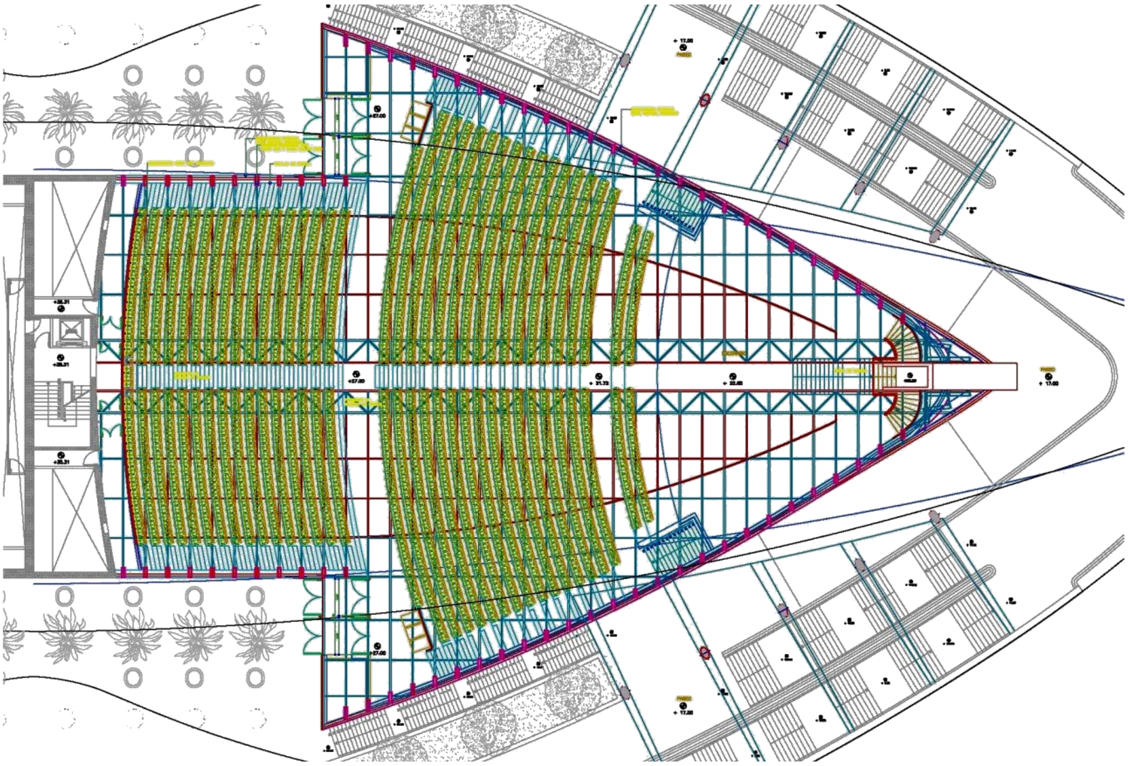


Figure D 16 Palau de les Arts_Plan of the Auditorium
("Palau de les Arts, Valencia," 2008)

D 1.2.1 Basic Characteristics of the Auditorium.

Table 1.2-I displays the dimensions, surface area and volume of the Auditorium and indicates its seating capacity for concert and opera.This is illustrated in Figure D 17 Table 1.2- I Palau de les Arts_Audithorium

TABLE 1.2.I	
DIMENSIONS	
Hall:	minimum width 28.3 m maximum width 41 m width in 2nd stalls 26 m length 50.8 m average height in 1st audience area 19.1 m average height in 1st audience area 14.4 m
Stage:	minimum width 10 m maximum width 25 m length 14.5 m average height 16.5 m
Orchestra Pit:	minimum width 20.4 m maximum width 23.2 m depth 3.1 m
Separation between rows:	0.9 m
Distance between the edge of the stage and the furthest auditor:	38 m
SURFACE AREA	
Stage:	250 m2
Orchestra Pit:	74 m2
Hall:	
1st Audience area:	698 m2
2nd Audience area:	390 m2
TOTAL:	1088 m2
VOLUME	
Hall:	21600 m3
SEATING CAPACITY	
For concerts:	1458 seats
For opera:	1384 seats

Figure D 17 Table 1.2- I Palau de les Arts_Audithorium
("Palau de les Arts, Valencia," 2008)

D 1.2.2 Uses and criteria

The Auditorium has become a multipurpose Hall which is used for symphonic concerts, conferences, congresses as well as concerts with amplified music (not hard rock), regional dances, ballets, recitals and zarzuelas, Baroque opera, cinema etc. The acoustic conditions necessary for a concert of symphonic music are obviously very different from those of a concert with amplified music and even more so for a congress.

This makes it imperative to install in the Hall a system of variable absorption which will adapt the acoustics within the hall to the different activities. Such a system has not been installed. The hall as designed by the architect also presents certain limitations and as a result it is used mainly for concerts.

Table 1.2-II lists the criteria applicable for the two most contrasting uses (symphonic concerts and amplified music or speech). The other activities require reverberation times in between these two and with the help of a system of variable absorption these changes can be achieved.Figure D 18 Table 1.2-II Palau de les Arts_Auditorium two major uses: unamplified symphonic orchestra and amplified music or speech

TABLE 1.2-II	
ACOUSTIC CRITERIA	
Reverberation Time (T60)	
Amplified Music/Speech Mode:	1.1 – 1.2 ss (occupied)
Concert Mode:	1.9 – 2.0 (occupied)
EDT:	The optimum is adjusted to the classic T60
Musical clarity: C50: C80:	 between -5 and +1 between -2 and +2
Total Level:	>=0
Speech intelligibility:	>=90%
Background Noise:	NC-15

Figure D 18 Table 1.2- II Palau de les Arts_Auditorium two major uses: unamplified symphonic orchestra and amplified music or speech
("Palau de les Arts, Valencia," 2008)

D 1.2.3 Interior Finishes

Table 1.2-III shows the interior finishes for the Auditorium. The seats are covered in leather, and were designed by the Architect Santiago Calatrava.Figure D 19 Table 1.2- III Palau de les Arts_Auditorium material application

TABLE 1.2-III PALAU DE LES ARTS INTERIOR FINISHES OF THE AUDITORIUM	
SURFACE	MATERIAL
CEILING 1	Double glazing with an air space equal or more than 10mm
CEILING 2	Wood lath + Plywood Panel 10mm mounted on joists with a cavity greater than 50mm
REFLECTORS	Wood >20 mm
BACK WALL	Wood lath + Rock Wool 40mm 50% perforation Covered with broken ceramic pieces (*trencadis*)
LATERAL WALLS OF BALCONIES (AMPHITHEATRE)	Wood lath + rock wool 40mm 50% perforation Gypsum board >30 mm
ENTRANCE WALLS	Wood lath+ rock wool 40mm 50% perforation Gypsum board >30 mm
LATERAL WALLS OF REAR STALLS	Wood lath + Plywood Panel 40mm 50% perforation Gypsum board >30 mm
LATERAL WALLS FOR THE REST OF THE STALLS	Wood lath + Plywood Panel 10mm mounted on joists with a cavity greater than 50mm. Gypsum board >30mm
CORRIDORS AND STAIRS	Marble
STAGE	Wood 40mm on joists
CENTRAL CORE (ESPINA CENTRAL)	2 slabs of plasterboard (2*13mm) with a cavity of 50mm filled with fibre

Figure D 19 Table 1.2- III Palau de les Arts_Auditorium material application ("Palau de les Arts, Valencia," 2008)

Figure D 20 Palau de les Arts_Longitudinal section Auditorium and Figure D 21 Palau de les Arts_View of Auditorium show real inside view into space of Auditorium.

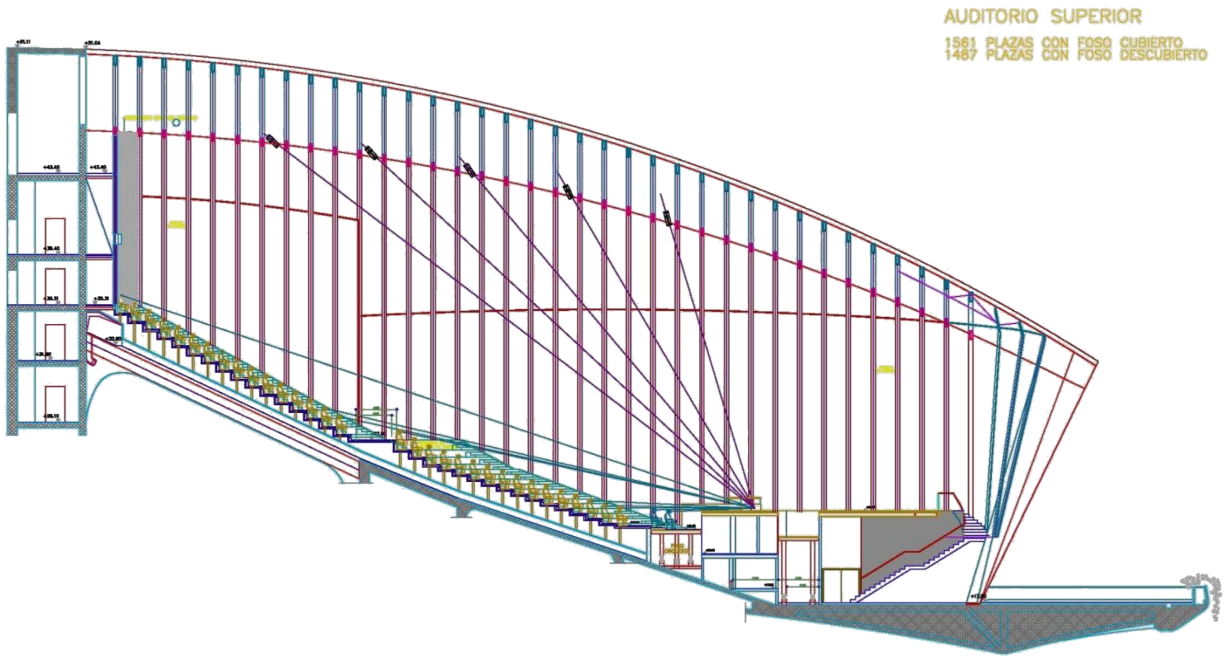


Figure D 20 Palau de les Arts_Longitudinal section Auditorium

("Palau de les Arts, Valencia," 2008)

Figure D 21 Palau de les Arts_View of Auditorium

("Palau de les Arts, Valencia," 2008)

D 1.3 Palau de les Arts _hall for chamber music. Example of chamber music and conference space for 400 auditors

Given its size this Hall was conceived as a venue for chamber music or small groups of musicians or soloists

The Hall for chamber music is also called MASTER CLASS ROOM with seating for 400, is located on the western side of the building. Access to it is by the main side stairs which converge on the building's different terraces. Over this hall there is a cafeteria and below this are the dressing rooms. The Master Class Room is specially designed for live performances by small music ensembles and can be used for holding conferences, congresses, press conferences, etc.

Figure D 22 Palau de les Arts_Master Class room inside view of auditorium spaceand Figure D 23 Palau de les Arts_Master Class Room_inside view on the stage

Figure D 22 Palau de les Arts_Master Class room inside view of auditorium space

("Palau de les Arts Reina Sofía opera house. Valencia," 2008.)

Figure D 23 Palau de les Arts_Master Class Room_inside view on the stage

("Palau de les Arts Reina Sofía opera house. Valencia," 2008.)

Figure D 24 Palau de les Arts_Plan of Chamber Music Hall and Figure D 25 Palau de les Arts_Longitudinal section of the Chamber Music Hall

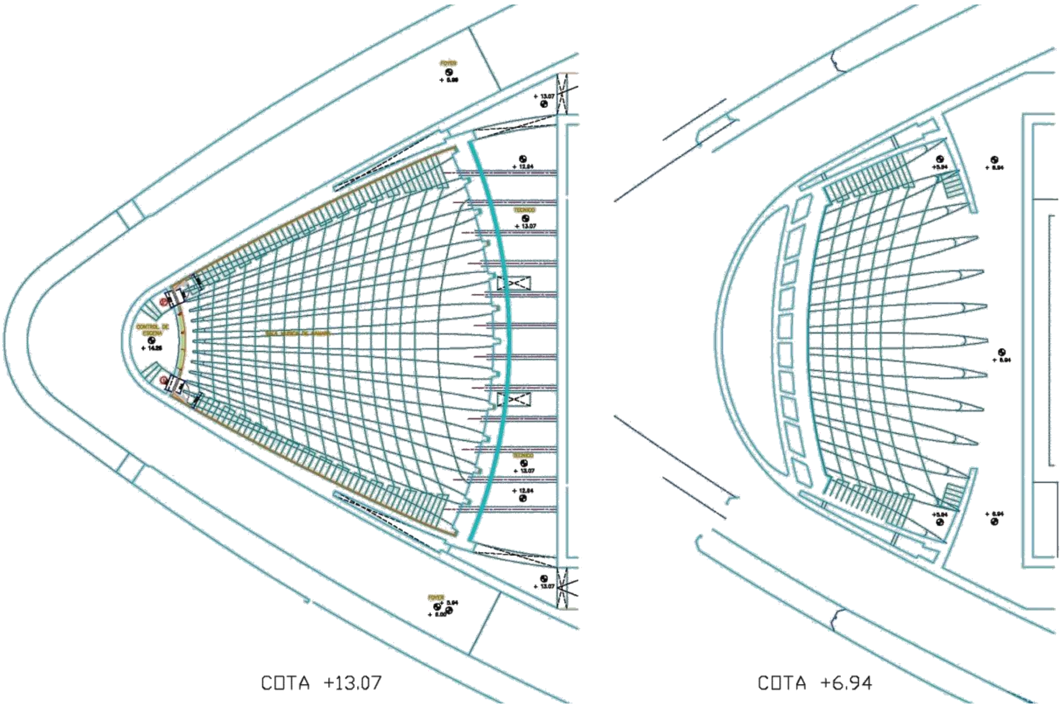


Figure D 24 Palau de les Arts_Plan of Chamber Music Hall

("Palau de les Arts, Valencia," 2008)

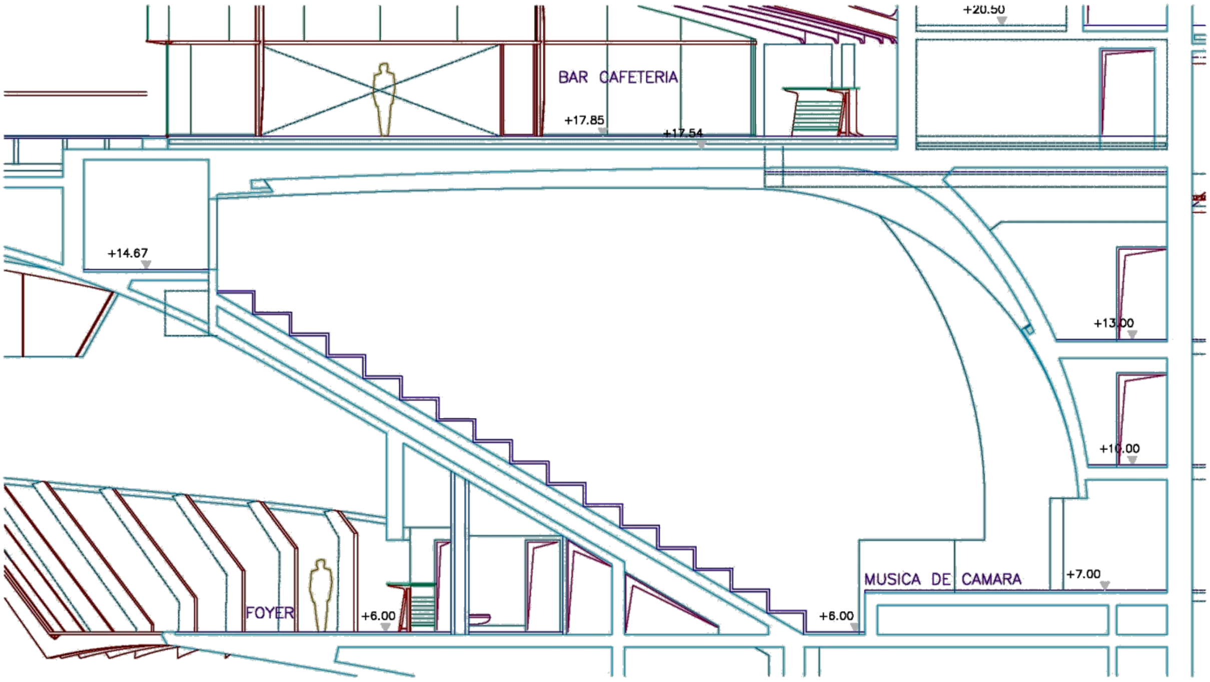


Figure D 25 Palau de les Arts_Longitudinal section of the Chamber Music Hall
("Palau de les Arts, Valencia," 2008)

D 1.3.1 Basic characteristics of the Hall

Table 4-1 shows the dimensions, surface areas, volume and seating capacity of the Hall in Figure D 26 Table 1.3- I Palau de les Arts_Chamber Music Theater basic dimensional parameters is shown in Figure D 26 Table 1.3- I Palau de les Arts_Chamber Music Theater basic dimensional parameters

TABLE 1.3-I	
DIMENSIONS	
Stage:	width 13.3 m depth 7.2 m
Hall:	maximum width 24.4 m minimum width 7 m length 19 m minimum height 2.5 m maximum height 9.6 m
SURFACE AREA	
Stage:	104 m2
Hall:	290 m2
VOLUME	
Total:	2200 m3
SEATING CAPACITY	
Total:	402 seats

Figure D 26 Table 1.3- I Palau de les Arts_Chamber Music Theater basic dimensional parameters ("Palau de les Arts, Valencia," 2008)

D 1.3.2 Uses and criteria

The Hall is designed for concerts of small groups of musicians or soloists, for Master Classes and conferences. The acoustics of the Hall must therefore accommodate to the music to be performed.

Table 1.3-II lists the Acoustic Criteria applicable to this type of Hall is shown in Figure D 27 Table 1.3- II Palau de les Arts_Chamber music for soloist uses

TABLE 1.3-II	
ACOUSTIC CRITERIA	
Reverberation Time (T60)	1,4 – 1,5 ss. (occupied)
EDT:	The optimum adjusts to T60 classic
C50:	Between -5 and +1
C80:	Between -2 and +2
Total level:	>=0
Speech Intelligibility:	>=90%
Background Noise:	NC-15/NC-20

Figure D 27 Table 1.3- II Palau de les Arts_Chamber music for soloist uses

("Palau de les Arts, Valencia," 2008)

D 1.3.3 Interior Finishes

Table 1.3-11 displays the interior finishes of the Chamber Music Hall. The seats are covered with leather, the design of the Architect Santiago Calatrava. Figure D 28 Table 1.3-III Palau de les Arts_Chamber music hall material application

TABLE 1.3-III PALAU DE LES ARTS INTERIOR FINISHES OF THE chamber music hall	
SURFACE	MATERIAL
CEILING	Painted thin concrete
CEILING BEAM FILLS	Suspended ceiling of dense wood backing and 20 mm absorbent rock wool material
STAIRS AND CORRIDORS	Marble
LATERAL WALLS	Wood lath + Plywood Panel 10 mm mounted on joists with cavity greater than 50 mm
REAL WALL	Painted smooth concrete
STAGE	40mm wood on joists

Figure D 28 Table 1.3-III Palau de les Arts_Chamber music hall material application

("Palau de les Arts, Valencia," 2008)

D 1.4 Palau de les Arts _experimental theatre. Example of opera space for 400 auditors

The fourth Hall within the Palau de les Arts was designed for use as a theatre and for opera as it includes an orchestra pit and a stage, although the latter does not have the necessary height to allow for a catwalk.

CHAMBER THEATRE. Exhibition hall. The Applied Arts building is adjacent to the Palau and forms the south-west boundary of the complex. The building is independent of the Palau de les Arts Reina Sofia. Its main feature is a hall for experimental theatre that can accommodate an audience of 400, where the Professional Training Centre will be located.

Figure D 29 Palau de les Arts_Experimental theatre Martin y Soler_inside view

Figure D 29 Palau de les Arts_Experimental theatre Martin y Soler_inside view

("Palau de les Arts Reina Sofía opera house. Valencia," 2008.)

Figure D 1 Longitudinal section of the Palau de les Arts and Figure D 32 Table 1.4- I Palau de les Arts_Experimental Theatre basic dimensional information

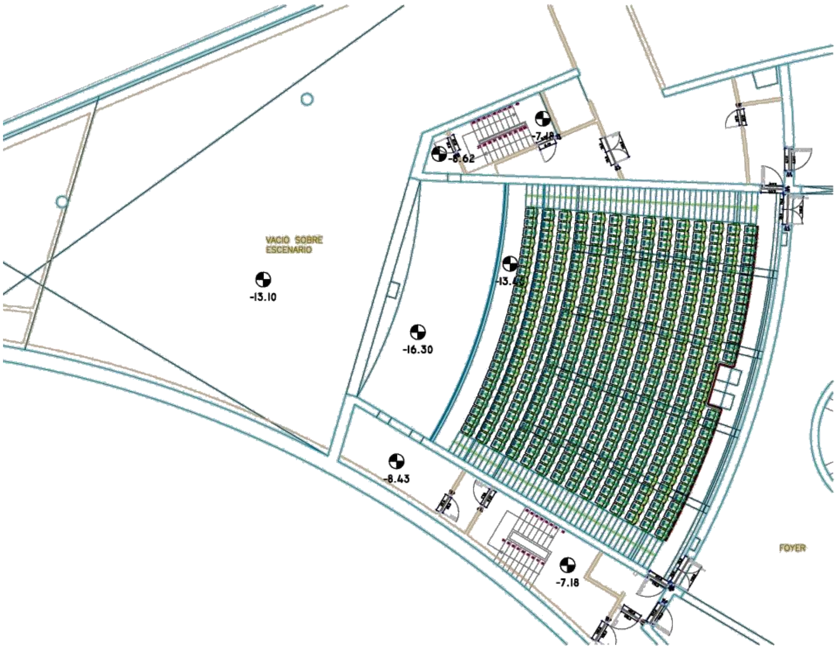


Figure D 30 Palau de les Arts_Plan of the Experimental Theatre

("Palau de les Arts, Valencia," 2008)

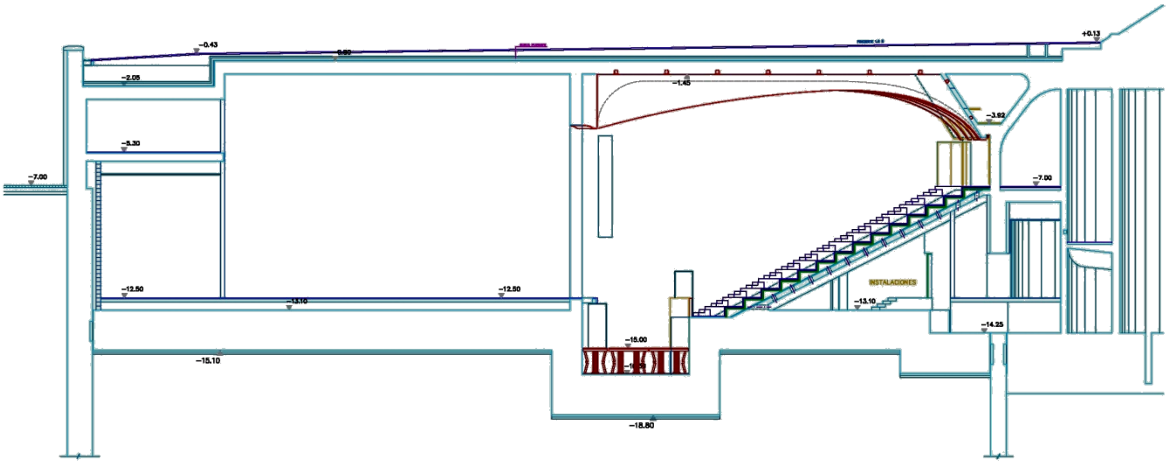


Figure D 31 Palau de les Arts_Longitudinal section of the Experimental Theatre ("Palau de les Arts, Valencia," 2008)

D 1.4.1 Basic Characteristics of the Theatre

Table 1.4-I presents the dimensions, surface areas, volume and seating capacity of the Hall and presents the dimensions and surface area of the orchestra pit.Figure D 32 Table 1.4- I Palau de les Arts_Experimental Theatre basic dimensional information

TABLE 1.4-I	
HALL	
DIMENSIONS	
Apron	1,3 m
Hall	minimum width 12 m maximum width 21.5 m length 20.7 m average height 8.3 m
Separation between rows:	0.9 m
Distance between Proscenium opening and furthest auditor	19 m
SURFACE AREA	
Apron	197 m2
Floor area	263 m2
VOLUME	
Total	2900 m3
SEATING CAPACITY	
Total	425 seats
ORCHESTRA PIT	
Dimensions	minimum width 12 m maximum width 13 m length 5.1 m
Surface Area	64 m2

Figure D 32 Table 1.4- I Palau de les Arts_Experimental Theatre basic dimensional information ("Palau de les Arts, Valencia," 2008)

D 1.4.2 Uses and criteria

This Hall is intended to be used for small size operas, auditions and rehearsals for the Academy of Perfection, for Drama, Ballet and Dance.

Table 1.4-II presents the Acoustic criteria applicable to this Hall.Figure D 33 Table 1.4- II Palau de les Arts_Experimental theatre for drama, ballet, dance and small opera use

table 1.4-II	
ACOUSTIC CRITERIA	
Reverberation Time (T60)	1.2 – 1.3 ss. (Occupied)
EDT:	The optimum adjusts to T60 classic
C50:	Between -5 and +1
Total level:	>=0
Speech Intelligibility:	>=90%
Background noise:	NC-20

Figure D 33 Table 1.4- II Palau de les Arts_Experimental theatre for drama, ballet, dance and small opera use

("Palau de les Arts, Valencia," 2008)

D 1.4.3 Interior Finishes

Table 1.4-III shows the interior finishes of the Experimental Theatre. The seats are covered with leather, the design of the Architect Santiago Calatrava.Figure D 34 Table 1.4- III Palau de les Arts_Experimental Theatre material application

TABLE 1.4-III PALAU DE LES ARTS INTERIOR FINISHES EXPERIMENTAL THEATRE	
SURFACE	MATERIAL
CEILING	Painted thin concrete
REAR WALL	Wood lath + Rock wool 40 mm 50% perforation
LATERAL WALLS	Wood lath + Plywood panel 10 mm mounted on joists with cavity greater than 50 mm
REST OF WALLS	Painted thin concrete

Figure D 34 Table 1.4- III Palau de les Arts_Experimental Theatre material application

("Palau de les Arts, Valencia," 2008)

D 1.5 Palau de les Arts _orchestra rehearsal hall. Example of orchestra rehearsal space

This Hall is situated between the Auditorium and the Main Hall and is designed to be used daily as the rehearsal room for the Palau de les Arts Orchestra.

Figure D 35 Palau de les Arts_Plan of the Orchestra Rehearsal Hall and Figure D 36 Palau de les Arts_Longitudinal section of the Orchestra Rehearsal Room and Figure D 37 Palau de les Arts_View of Orchestra Rehearsal Hall

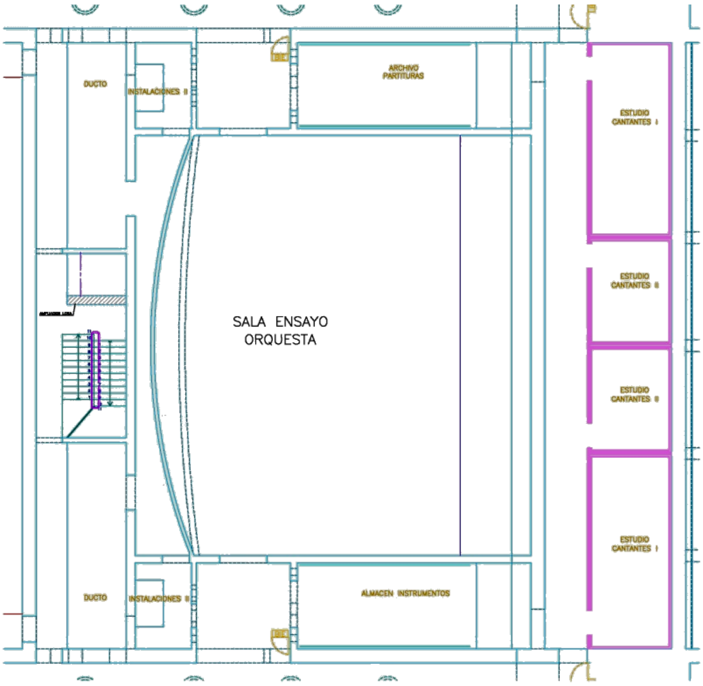


Figure D 35 Palau de les Arts_Plan of the Orchestra Rehearsal Hall ("Palau de les Arts, Valencia," 2008)

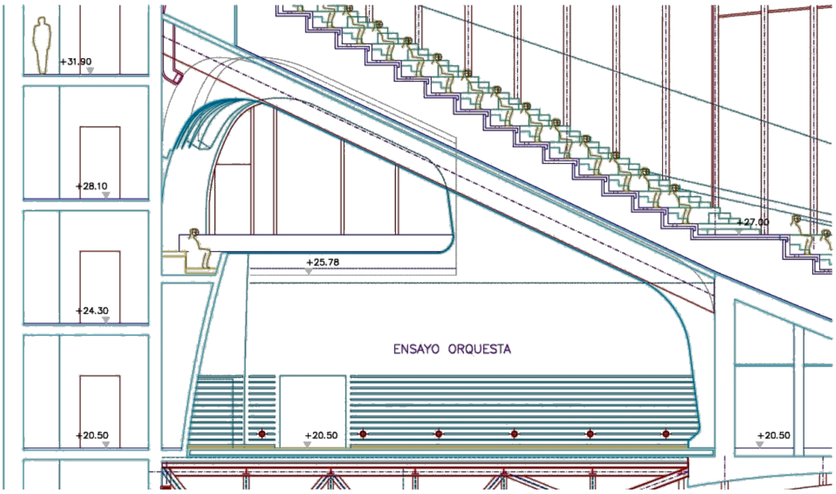


Figure D 36 Palau de les Arts_Longitudinal section of the Orchestra Rehearsal Room ("Palau de les Arts, Valencia," 2008)

Figure D 37 Palau de les Arts_View of Orchestra Rehearsal Hall ("Palau de les Arts, Valencia," 2008)

D 1.5.1 Basic characteristics of the Hall

Table 1.5-I shows the dimensions, surface area and volume of the Orchestra Rehearsal Hall. This is shown in Figure D 38 Table 1.5- I Palau de les Arts_Orchestra rehearsal hall basic dimensional parameters

TABLE 1.5-I ORCHESTRA REHEARSAL HALL	
Dimensions:	width 18 m length 16 m minimum height 5.4 m maximum height 11.3 m
Floor surface:	288 m2
Volume:	2600 m3

Figure D 38 Table 1.5- I Palau de les Arts_Orchestra rehearsal hall basic dimensional parameters ("Palau de les Arts, Valencia," 2008)

D 1.5.2 Uses and criteria

In addition to orchestra rehearsals this Hall, because of its size, can also be used for chamber music performances or recitals, in which case the audience is seated on movable seats.

Table 1.5-II indicates the Acoustic Criteria applicable to the Hall on Figure D 39 Table 1.5-II Palau de les Arts_Orchestra rehearsal use

table 1.5-II	
ACOUSTIC CRITERIA	
Reverberation Time (T60) Variable Absorption:	0.9 -1.4 ss (occupied)
EDT:	The optimum adjusts to T60 classic
C50:	Between -5 and +1
Background noise:	NC-20

Figure D 39 Table 1.5-II Palau de les Arts_Orchestra rehearsal use ("Palau de les Arts, Valencia," 2008)

D 1.5.3 Interior Finishes

Table 6-III presents the interior finishes of the Orchestra Rehearsal Hall. Figure D 40 Table 1.5- III Palau de les Arts_Orchestra rehearsal material application

TABLE 1.5-III PALAU DE LES ARTS INTERIOR FINISHES OF THE orchestra rehearsal hall	
SURFACE	MATERIAL
CEILING	Suspended gypsum board 26 mm and wood lath hiding rock wool absorbent material
LATERAL AND REAR WALLS	Concrete – Curtains and wood laths hiding rock wool panels
FLOOR	Wood platform 20 mm on joists
REST OF WALLS	Thin concrete

Figure D 40 Table 1.5- III Palau de les Arts_Orchestra rehearsal material application ("Palau de les Arts, Valencia," 2008)

D 1.6 Palau de les Arts _choir and ballet rehearsal halls. Example of choir rehearsal hall

These Halls are situated on the same level as the Orchestra Rehearsal Hall and are designed for daily rehearsals of the Choir and Ballet of the Palau de les Arts and other invited groups.

Figure D 41 Palau de les Arts_Plan of the Choir and Ballet Rehearsal Halls

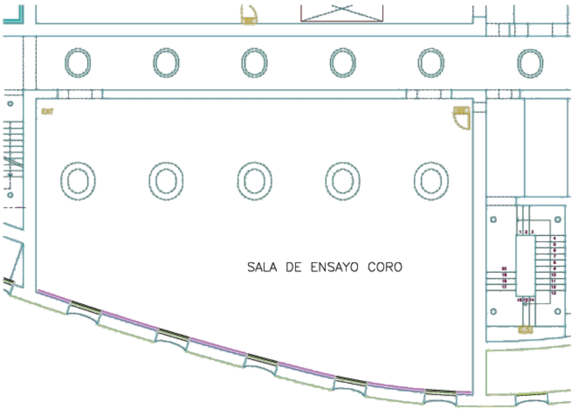


Figure D 41 Palau de les Arts_Plan of the Choir and Ballet Rehearsal Halls
("Palau de les Arts, Valencia," 2008)

D 1.6.1 Basic characteristics of the Halls

Figure D 42 Table 1.6-I Palau de les Arts_ Choir and ballet rehearsal hall basic dimensional parameters

("Palau de les Arts, Valencia," 2008)

Uses and criteriaTable 1.6-I shows the dimensions, surface areas and volume of the choir and ballet rehearsal halls

TABLE 1.6-I CHOIR AND BALLET REHEARSAL HALL	
Dimensions:	width 20 m length 10 m height 5 m
Floor surface:	200 m2
Volume:	1000 m3

Figure D 42 Table 1.6-I Palau de les Arts_ Choir and ballet rehearsal hall basic dimensional parameters
("Palau de les Arts, Valencia," 2008)

D 1.6.2 Uses and criteria

Because of their size these halls can also be used for auditions and presentations.

Figure D 43 Table 1.6-II Palau de les Arts_Choir and Ballet rehearsal hall use and criteriaTable 1.6-II indicates the acoustic criteria applicable to these Halls

table 1.6-II	
ACOUSTIC CRITERIA	
Reverberation Time (T60) Variable Absorption:	0.8 -1.2 ss (occupied)
EDT:	The optimum adjusts to T60 classic
C50:	Between -5 and +1
Background noise:	NC-20

Figure D 43 Table 1.6-II Palau de les Arts_Choir and Ballet rehearsal hall use and criteria ("Palau de les Arts, Valencia," 2008)

D 1.6.3 Interior Finishes

Figure D 44 Table 1.6-III Palau de les Arts_Choir and ballet rehearsal material applicationTable 1.6-III shows the interior finishes of the choir and ballet rehearsal hall.

TABLE 1.6-III PALAU DE LES ARTS INTERIOR FINISHES OF THE orchestra rehersal hall	
SURFACE	MATERIAL
CEILING	Suspended gypsum board 26 mm and wood lath hiding rock wool absorbent material
WALLS	Gypsum board 30 mm - curtains
FLOOR	Wood platform 20 mm on joists

Figure D 44 Table 1.6-III Palau de les Arts_Choir and ballet rehearsal material application ("Palau de les Arts, Valencia," 2008)

D 1.7 Palau de les Arts _results and comments

Figure D 45 Tables 1.7 I-V Palau de les Arts_results.Tables 1.7-I to 1.7-V summarize the final results: the detailed results are property of the client and cannot be divulged.

TABLE 1.7-I	
RESULTS – MAIN HALL ÓPERA	
T60 at 500Hz and 1000Hz	
Empty	1.8ss
Occupied	1.5ss
Warmth	1.3
Brilliance at 4000Hz	0.85
EDT:	1.7
C50:	-2 to +1 dB
Background Noise:	27.8
CONCERT	
T60 at 500Hz and 1000Hz	
Empty	2.1ss
Occupied	1.75ss
EDT:	1.7
C80:	-1 to 3 dB
Background Noise	27.8

TABLE 1.7-II	
RESULTS – AUDITORIUM	
T60 at 500Hz and 1000Hz	
Empty	1.7ss
Occupied	1.4ss
Warmth	1.25
Brilliance at 4000Hz	0.8
EDT:	1.6
C50:	-3 to 4 dB
C80	-2 to +3 dB
Background Noise (*)	33,0 dB

TABLE 1.7-III	
RESULTS – CHAMBER MUSIC HALL	
T60 at 500Hz and 1000Hz	
Empty	1.4ss
Warmth	1.15
Brilliance at 4000Hz	0.75
EDT:	1.4
Background Noise	29.0 dB

TABLE 1.7-IV	
RESULTS – EXPERIMENTAL THEATRE	
T60 at 500Hz and 1000Hz	
Empty	1.4 ss
Warmth	1.25 ss
Brilliance at 4000Hz	0.82 ss
EDT:	1.25 ss
Background Noise	31.0 dB

TABLE 1.7-V	
RESULTS – REHEARSAL HALLS	
T60 at 500Hz and 1000Hz Vacías	
Orchestra	1.2ss
Choir	1.1ss
Ballet	1.1ss
Background Noise	
Orchestra	30.0 dB
Choir	28.5 dB
Ballet	29.0 dB

Figure D 45 Tables 1.7 I-V Palau de les Arts_results

("Palau de les Arts, Valencia," 2008)

The overall results achieved meet the criteria set out for each Hall and the Palau de Les Arts has received acclaim for its acoustics.

It is true that there have been complaints about the Auditorium, for its acoustics and also for the indecision over what activities should take place there. It is important to point out, however, that in the case of the Auditorium no system of variable acoustics was installed and that the insulation offered by the vertical and horizontal building elements was reduced to comply with safety regulations. In addition there is, even today, no clear use defition.

SECTION D 2 Overview _Arena, Zagreb

See generally ("Arena, Zagreb," 2009.), (Tomić).

Arena Zagreb is the multipurpose indoor arena located in the south-western part of Zagreb, Croatia, that was primarily planned as a central sports hall for hosting the 2009 World Men's Handball Championship.

The location of Arena Zagreb is the south entrance into the Croatian capital city, Zagreb.

It was built and opened in the year 2009.

The designer of the facility was the Croatian firm UPI2M.

It was built as one of 6 sport facilities for purpose of the world handball championship. After the handball championship finished, Arena Zagreb hosted many other purposes as well as sports. It is now a venue for contemporary music concerts, congresses, trade fairs and similar events.

Since venues of such capacity cannot be profitable if capable of hosting only sporting competitions, the Arena was designed as a multifunctional hall with all spatial and functional characteristics that enable maximal flexibility and allow for numerous events. This influence is mostly present in the flexibility of the grandstand, in preserving sufficient and various spaces reserved for athletes, other performers and event managers, in providing simple and fluid visitor circulation from entry point to the seat on the stand and offering various catering facilities, in dividing the whole building in smaller mutually independent spatial zones that can be used separately, in acoustic interventions inside the hall shell and at last in suring sufficient bearing capacity of the steel roof structure capable for suspension of additional scene equipment.

This multi-functional venue is composed of 6 floor levels, covering total GBA of 90.340 m^2 on a 29.540 m^2 footprint. Functional area partition follows the circulation routes of different users.

The underground level is mainly garage space with access by 2 car ramps with a total parking capacity of 956 vehicles (additionally, the 3,300 parking places in the future nearby shopping centre will be used as well).

On the ground floor the field of play with all necessary athletes-, performers-, judges-, trainer’s facilities are positioned as well as rentable office space. The central arena’s court can be transformed depending on the event.

The 1st floor represents the main pedestrian approach level with four main entrances to the venue. The visitors enter the grandstand directly from this level or by rising to the

3rd floor passing through the circular halls with numerous catering facilities, which are partly connected to the pedestrian platform and usable also independently from the venue.

The 2nd floor is reserved for VIP-guests and media stuff having their own fully equipped spaces with possibility of multi-functional usage also for conferences, workshops or congresses. The restaurant on this level offers a direct view to the court and can be used during events, but also independently.

The 4th floor is reserved for technical equipment, and is also connected to catwalks distributed underneath the roof and used for maintenance of lighting and loudspeaker devices assembled along them.

All described zones are mutually independent and equipped with a sufficient number of separated accesses with very clear user's circulation system - quick and easy entering and exiting is sured, and mixing user circulation routes are avoided.

The unique shape of this building is strongly inspired by its significance in the city context, but also by its mega-structural characteristics that predefined main bearing elements. Shaped as a protective rib cage around the building essence – the court, 86 large pre-stressed, pre-fabricated concrete curved columns form the main façade, mutually connected by an illuminated semi-translucent polycarbonate envelope that enables various light effects.

The elevated pedestrian access platform connects the building through several pedestrian ramps and staircases to the existing surrounding as well as to the neighbouring new planned shopping / entertainment centre, representing by its emphasis the future gathering point.

The example of last Olympic Games in Beijing demonstrates the spectacular and theatrical context of contemporary sporting events, which requires adequate spatial response in architectural solutions for hosting venues. On the other hand, their size in comparison with the standard city scale, also implicates the significance they have in the global city image. However, it takes much more: by well designed shaping synergized with structural requirements and urban context all conditions are fulfilled for iconic recognition and for access to the list of city emblems. Hopefully Arena Zagreb achieved that intention.

Calculation of reverberation time was carried out on the computer program EASE 3.2. The main demand made on such a primarily sport facility was to obtain a reverberation time of 1.8 s up to 2 s. This demand was calculated for unoccupied space. When occupied reverberation time sinks due to the greater absorption created by auditors.

2 types of scenario were calculated: sports events and concert events. Results made evident that for concert purpose on the rear walls housing the retractable seats additional acoustical absorption should be used in the form of flexible curtains. The problem does not occur when retractable seats are used, in other words occupied.

Following are pictures that represent the building Arena Zagreb. Pictures are as follows:Figure D 46 Arena Zagreb_plan view, Figure D 47 Arena Zagreb_cross-section, Figure D 48 Arena Zagreb_inside view, Figure D 49 Arena Zagreb_ outside view.

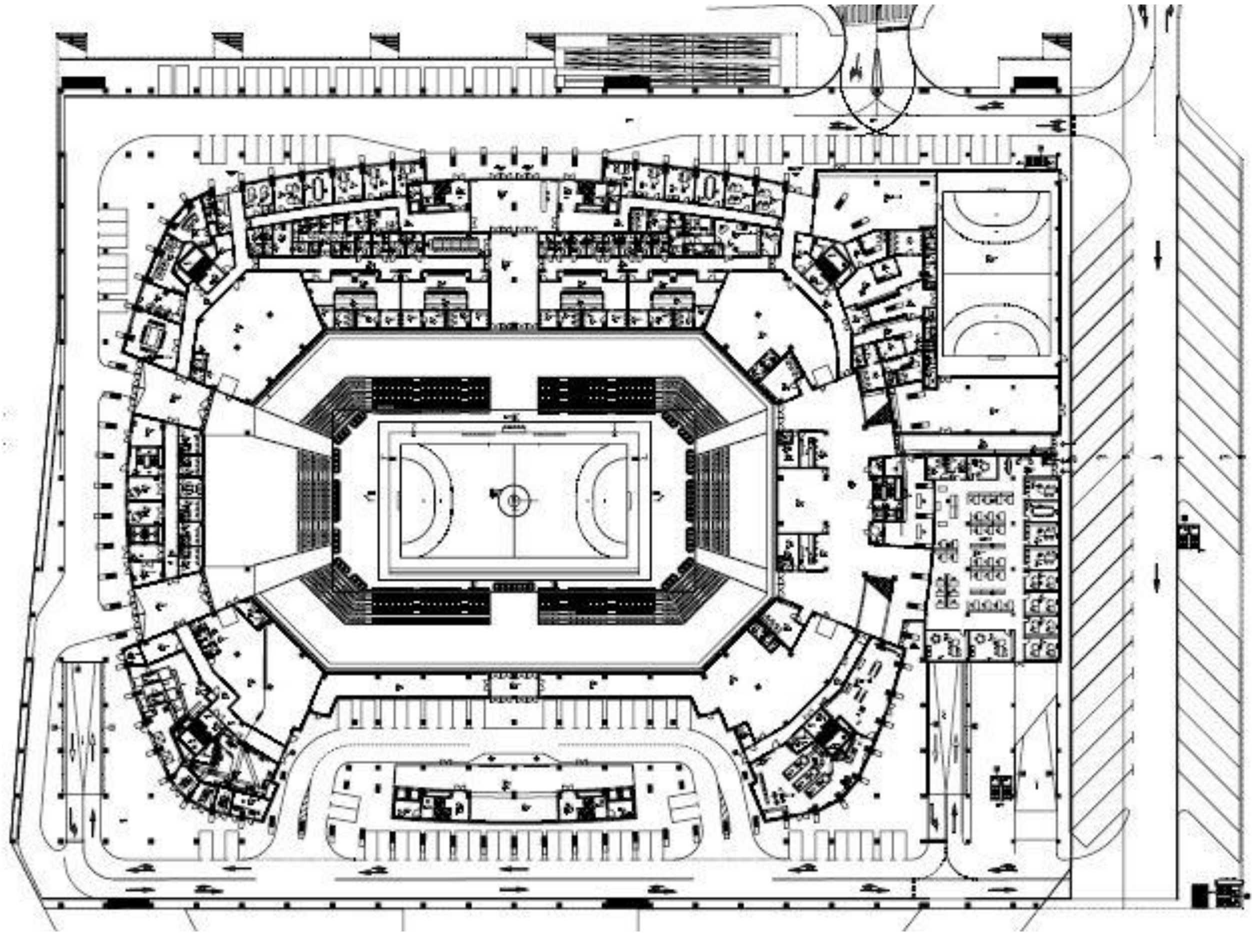


Figure D 46 Arena Zagreb_plan view

("Arena, Zagreb," 2009.)

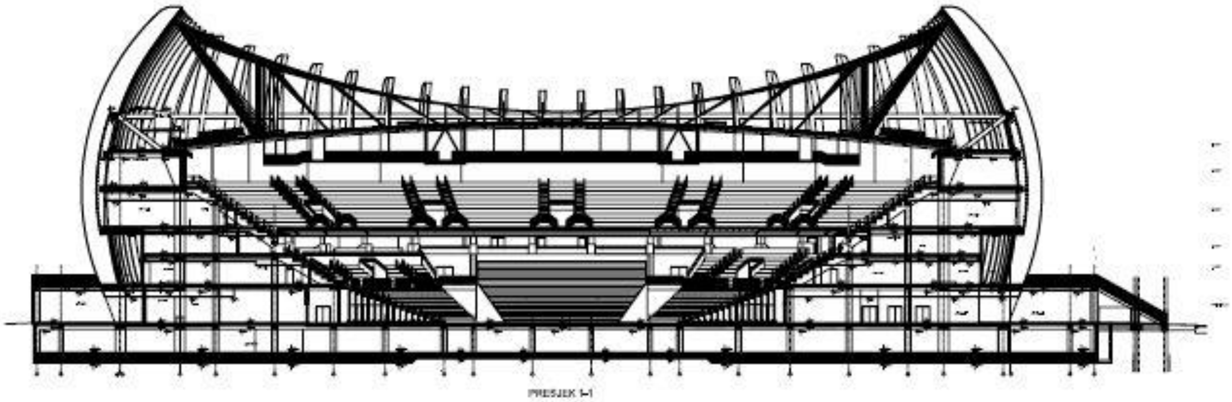


Figure D 47 Arena Zagreb_cross-section

("Arena, Zagreb," 2009.)

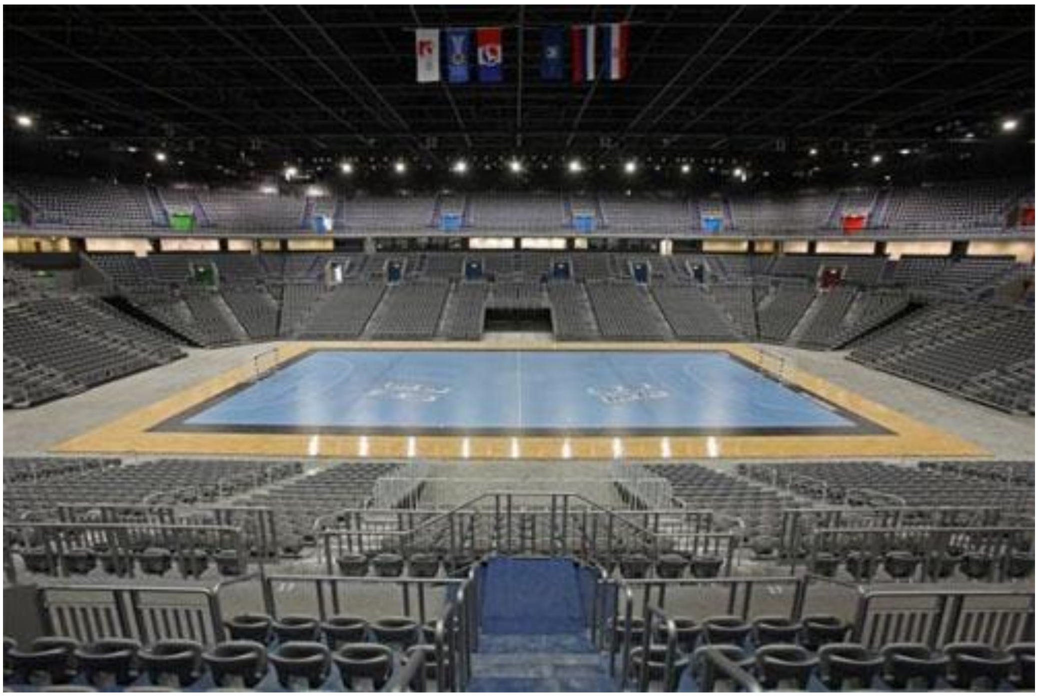


Figure D 48 Arena Zagreb_inside view

("UPI-2M Project, Arena Zagreb in Croatia," 2009)

Figure D 49 Arena Zagreb_ outside view

("UPI-2M Project, Arena Zagreb in Croatia," 2009)

D 2.1 Arena, Zagreb. Example of sports arena used for acoustic events for 15000 auditors

D 2.1.1 Basic characteristics of the Hall

The flexibility of this venue is most evident by the grandstand transformability. According to the main seating configuration for handball competitions (also basketball, volleyball, tennis and indoor football) the grandstand covers 15,024 seats, 151 of which are for disabled auditors/spectators. The remaining part of the grandstand is fixed and incorporates 10,336 seats divided between the lower and upper stand. This includes 314 VIP seats in front of the VIP boxes. The lowest part of the grandstand is a zone of 15-row retractable stands (26-row at the northern side - potential stage position) with 4,556 seats (plus additional 132 free seats at the court level). All together, 15,024 seats. Additional seats can be chairs brought into the Arena, or more probably, the playing area is going to be used for standing places in the pop concert scenario.

Figure D 50 Table 2-I_Main hall basic dimensional parameters

TABLE 2-I ORCHESTRA REHEARSAL HALL	
Dimensions:	width 130.5 m length 153.7 m Max height 27.225 m
Floor surface:	20057.85 m2
Volume:	207109.6 m3

Figure D 50 Table 2-I_Main hall basic dimensional parameters

Table made by the author using reference: ("Arena, Zagreb," 2009.) documentation

D 2.1.2 Uses and criteria

Arena Zagreb is also designed for hosting numerous other sporting, cultural, entertainment and business events such as indoor football, basketball, volleyball, indoor athletics, hockey, other sporting competitions and also concerts, exhibitions, fairs, congresses and family shows. In order to adequately accommodate such events, numerous supporting facilities are provided - catering, sanitary, cloak room, office and similar spaces; also the small training hall with its own facilities and smaller multi-functional spaces on the 2nd floor can be used for mini congresses, workshops and / or lectures.

For other sports events (table tennis, badminton, gymnastic, boxing, wrestling...) there is a possibility of putting additional seats at the court level, and for indoor athletics, all telescopic stands must be retracted, which reduces the capacity.

Cultural and entertainment events (concerts, exhibitions, fairs…) demand the grandstand to be transformed in line with the requirements of the event organizer, so the ground space can be used for additional seating or standing places.

If the nature of the event requires reduced seating capacity, the upper part of the stand can be enclosed using the suspended textile partitions.

Figure D 51 Table 2-II_Main hall two scenario use

TABLE 2-II	
CRITERIA – SPORT SCENARIO	
T60 at 500Hz and 1000Hz	
Empty	1.4ss
Occupied	0.9 s

TABLE 8-II	
CRITERIA – CONCERT SCENARIO	
T60 at 500Hz and 1000Hz	
Empty	1.4ss
Occupied	1.1ss

Figure D 51 Table 2-II_Main hall two scenario use

Table made by the author using reference: ("Arena, Zagreb," 2009.) documentation

D 2.1.3 Interior Finishes

Figure D 51 Table 2-II_Main hall two scenario use

TABLE 2-III ARENA_ZAGREB INTERIOR FINISHES OF THE MAIN HALL_SCENARIO SPORT	
SURFACE	MATERIAL
CEILING	Ceiling perforated panels 12,5% perforated trapezoid sheet metal. Inside is rock wool 20 mm.
LATERAL WALLS	Suspended wall perforated panels 100 mm thick with perforation of 39% and hiding rock wool absorber. Mat. and suspended gypsum board 100 mm thick with perforation of 39% hiding rock wool absorbent material
REST WALLS	Painted smooth concrete
FLOORING	wood on joists
COMMUNICATION_flooring	concrete
CURTAIN_only for concert scenario	textile

Figure D 52 Table2-III_Main hall material application

Table made by the author using reference: ("Arena, Zagreb," 2009.) documentation

D 2.2 Arena Zagreb _results and comments

For calculation of reverberation time a model was developed with the computer program EASE 3.2 and calculations were made using the Eyring equation.

The main demand made on such a primarily sporting facility was to obtain reverberation time of 1.8 s up to 2 s. This was the demand for unoccupied space. When occupied, reverberation time sinks due to the greater absorption created by auditors.

Material of the ceiling is totally absorbent, even more than 100%, in fact it is 115% percent absorbent, so the sound field develops only in the part of grandstand and playing court.

The main conclusion was that for spaces of huge volume it is not possible to obtain results on a fine scale. This means that only reverberation time can be taken in concern, while other characteristics of sound are not determined or even calculated. Volume is too much of an obstacle to get fine characteristics like clarity or G or distinctiveness, etc.

Also it is very important to clarify that this great volume of space should be amplified to obtain reasonable results.

Amplification on this project was determined to be unique for every different use and should be installed by the performer's team.

Two types of scenario were calculated: sports event and concert events. Results made it evident that for concert purposes on rear walls of retractable seats additional acoustical absorption should be used in the form of flexible curtains. The problem does not occur when retractable seats are used, in other words occupied.

For the sport scenario the unoccupied arena has reverberation of an average 1.8 s and when occupied 1.1 s.

For the concert scenario the reverberation of unoccupied space is an average of 1.7 s and for occupied 1.2 s.

Retractable or telescopic seats are absorbers in the middle field and this is useful when the arena is unoccupied. With occupancy this effect diminishes while auditors are more absorbent..

For the concert scenario, particularly for symphonic music, an acoustical shell should be provided by performer.

The purpose of showing these 7 examples is to reveal contemporary methodologies for obtaining quality sound bya consideration of the results. The examples show what criteria for high quality sound are used today in contemporary methodology for different functions. The results of contemporary methodologies are best heard, of course, but can also be presented by values, which is the case in this dissertation.

CONCLUSION OF DISSERTATION

Good acoustic design takes into account such issues as reverberation time; sound absorption of the finish materials; echoes; acoustic shadows; sound intimacy, texture and blend, as well as external noise. Architectural modifications (e.g., orchestral shells, canopies, and undulating or angled ceilings and walls) may act as focusing elements to improve sound quality.

This in fact is a correct term and it leads to the answer asked in the introduction. (Britannica; Web Page;*Architectural acoustics_term*). The solution of the issue as to whether it is possible to develop methods that can be guaranteed to provide spaces for superior sound lies in the elements that should be taken into consideration in the construction of such spaces. These steps are: firstly, the elements of sound; after that acoustics, after that methodology, and at last utilization in an evaluated and determined model and after that in real spaces.

The dissertation seeks an answer to the question whether methods could be developed that are going to generate spaces that provide superior sound. The whole concept of the dissertation was established to give a proper and reliable answer to this question.

Part A dealt with the basic physics of sound. Terms are explained from general physics to the term of sound level and how it is calculated and presented. The term sound level is further used in other parts.

In Part B the major terms in the science of room acoustics are explained. The most significant one is reverberation. In recent times other qualities of sound have been seen to contribute to the sound picture in a space.Unwanted spectra of sound effects are also discussed in this chapter. Also, protection against noise is the first and an obligatory step when dealing with architectural acoustics and it should be done completely before architectural acoustics is addressed. Noise protection is therefore an obligatory but not a sufficient condition for height quality sound. The next step involves using methods of architectural acoustics.

In Part C the standard method of present time for gaining quality sound is presented and questioned. In showing the historical development of the method it is evident that contemporary methods are upgraded versions of previous models and that they do not suppress the knowledge of the past. The most evident proof is that horseshoe shape is today the most appreciated shape for operas as it was in the past.

The process of designing an acoustically demanding space is in fact: the designer forms a space,and the acoustician gets the plan and makes a model and calculation. After that architect looks at the calculations and makes remarks and forms new demands. Again the acoustician gets a new plan and makes his calculations and brings it back for the architect’s approval and correction. This is a job of many steps forward and steps back until the final result, when the design is approved. Also, a real model can be generated to ease material selection and special interventions and real sound can be heard using headphones from the model. This is all made in very first part of planning, in preliminary planning. In this preliminary design, there is a non-standardised part of the procedure, when the architect and acoustician need to pick the model which is to be finalized.

After the planning phase, the work of the acoustician once again takes a part in the planning process, in the phase of the main project whenhe materials have to be calculated. After getting the documentation done once again the acoustician should monitor the installation of materials so that they could meet the requirements placed upon them. After the space is built measurements should be made by some method such as measuring the diffusion of sound from a point source or by some other method to show what the sound is really like in the space. After that, if they are necessary, and in most cases they are, improvements are made with the application of material.

In Part D contemporary standard methods results are shown through 7 different types of spaces. This part shows the result in quantitative terms with sound parameters as this is, in written form, the best possible way of presenting the methods. These examples show the grade of satisfactory sound quality by means data values in relation to the demand for superior sound. These examples also show how one model that the architect and acoustician have decided on is actually realized as a concrete space.

The exploration in area of non amplified sound showed implications for amplification itself. Namely, whether the sound is amplified or not, the major means of augmentation lies in reflection. As much reflection as possible will result in an augmented sound level. But it should be mentioned also here in conclusion that late reflections should be omitted so that there should not be any echo or mumbling effects.

The main leitmotiv of this dissertation was to explore what makes for quality sound and the answer is: reflection. When dealing with non-amplified space, the number, position and material of reflective surfaces is important and in the case of amplified sound the conclusion is that more reflective spaces are also helpful, just as in unamplified space and that more than one speaker should be used. It is better to use more not so very powerful speakers than a few speakers with great power.

In both amplified and not amplified sound there should be as much reflecting surface as possible because it is the conclusion drawn from the understanding of sound. The total sound field is the sum of sound levels from many sources of sound. Every reflection surface forms its new sound source and it is clear that more reflection surfaces form more sound sources , the result being a bigger sound level and a more homogenious sound. But it should be said once again that these sound sources are not added linearly but in a logarithmic manner.

When talking about modern electrical type of music in which sound is developed in the anticipation of the provision of electricity then amplification is quite a reasonable solution for obtaining the best results.

Furthermore, another answer to the question of methods also lies in the understanding that methods are going to be upgraded in time. Some qualities of sound are going to be questioned and some other perhaps found.

This will upgrade the designing methods that we now have. But that there will be constant upgrading does not derogate from the importance of the knowledge that more reflective areas give better sound. Reflectivity is incorporated in today’s methods and in the future it can be only presented or visualised in different form, or media, but the principle must stay the same. In other words, when using these methods that are known today we can surely build spaces of superior sound. Using new technologies would improve the sound quality in some degree. And using some future technologies, sound quality could be further improved but the basics of good sound will really continue to be found in historically developed sound quality methods that have been subject to constant improvement, with old methods never being entirely discarded. New findings and measurements of new sound qualities confirm that the existing methods are being borne out and developed, while not rejecting the achievements of the past.

Upgrading of contemporary methods in future will lie maybe in knowing better what is a perfect model and when to stop the process of the evaluation of models. This evaluation is in fact creativity and it is the question whether creativity will ever come down to a matter of calculation. My presumption is that creativity is never going to be determined with any kind of calculation, that creativity is above calculation and therefore evaluation process in future acoustical methodics will never be entirely defined. But the knowledge about sound is going to improve data inputs in selecting the final model, but ina asymptotic way, never reaching the goal, or in this case never finding a specific model, the best of all.

Before using methods for designing such places an architect should himself know elements of the science of acoustics or collaborate with an acoustician before embarking on design methods. Depending on the scale of quality that should be achieved, a superior, world recognised concert hall or a town hall, these roles change places. In most cases acousticians are not consulted because there is no such a demand. In that case, the degree of project sound success depends on architect’s knowledge and capabilities. If a building that needs to be recognised as a world leader in superior sound is to be built then acousticians must take a lead in designing and building the space and architects supervise only the major concept. Where the border is between the need for an acoustician and the absence of any such need is a difficult question. It is big enough to deserve exploration through a thesis to itself. That border depends on the cultural needs of citizans and technology state-of-the-art and the knowledge and capabilities of the architect. Acoustics calculations and applications are very expensive and that is the major reason for the infrequent usage of acoustic calculations.

Quality sound is the goal of every acoustician and in the process of getting that result done the acoustician needs to know all the sound qualities that are going to play a part. More specific, or purified elements that are part of methods for achieving spaces that provide superior sound are discussed as follows.

Acoustically demanding spaces can deal with sound in two basical ways. The first way is: developing natural sound field and the second one is: usage of amplification systems. Both ways need a great many reflection surfaces to develop into the kind of sound that listeners like the most. This is the sound of overall G of 82 dB, reverberation depending on type of performance, the feeling of spaciousness, intimacy, right clarity. These are the basic demands related to a high quality sound. Other qualities should also contribute to the general picture of sound in the space.

Acoustics is a science in development because nomenclature for lots of characteristics of sound is still not settled. In addition, only 30 years ago, only one characteristic of sound was used and that was reverberation. Today acousticians know a whole range of characteristics, but even today, they are still not prescribed as obligatory in design projects. These newest characteristics are in most cases used when wanting to design a space to be recognised as having among the best acoustics in the world.

Acoustics should not be in generally amplified with for symphonic purposes because the music itself in classical music developed in the human larynx and in instruments are propagated in the natural way of spreading sound waves. It makes no sense to make a space in which the classics are performed dead, after which it has to be equipped with amplifiers. This way, the natural sound field is translated into an electrical sound field. Classical music demands the natural development of sound field.

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