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Evaluation of the Effect of Dimensions and Geometry on Room Acoustics in Opera Houses, Concerts Halls and Theaters

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ABSTRACT

Today, population growth has resulted in an increase in building activities to satisfy the need for a variety of social gathering areas. In recent years, the architectural acoustic, acoustic science and hearing has become important. The principals of architectural acoustics were established in the 1920s, and these remain as an important project parameter to be resolved at the design stage in the case of opera houses, theaters, and concert and conference halls.
In this study, the importance of design in terms of volume, geometry and structural form for sound functionality is investigated.

Key Words: Room Acoustic, Acoustic Parameters, Volume and Geometry, Auditorium Design

1. INTRODUCTION

Today, technological advances, the rising population and developments in construction sector have resulted in the emergence of multi-functional spaces such as congress and exhibition venues, as well as such social and cultural facilities as theatres, concert halls, and opera and ballet houses. In the past, the acoustic design of such structures, there was in the area of science and engineering. Today, however, as the science of architectural acoustics has taken place. Successful auditoriums were developed on a trial-and-error basis. In the 19th century, halls with successful acoustic characteristics were taken as models for new constructions, although some led to disappointment, making it clear that scientific research was needed in this area.

The objective of study is to evaluate of the effect of the surface material, geometry and volume of the auditorium acoustical performance, employing acoustic parameters. The second part of the study is evaluating room acoustics between geometry and dimensions.

2. ROOM ACOUSTIC PARAMETERS

In the course of researches and empirical studies carried out into acoustic comfort and performance, certain parameters have been found influential.

2.1. Parameters Depending on Reverberation Time

2.1.1. Direct and Reverberant Sound

Sound coming from a source within a space comprises a sound field. As sound reaches the volume boundaries and reverberates, a reverberating sound field occurs. The energy density of the sound is the direct sound field created by a spherical source of sound:

$$E_d = (\Pi / c) / 4\pi r^2 \qquad (1.1)$$

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where; r : radial distance from the sound source (m)
Π : acoustic power output at the source comprising
c : the speed of sound (m / s)
E_d: energy density

When the equation for the Sabine reverberation time (1.4) and the equation for energy density are combined, the ratio of reverberating and direct sound energies is obtained;

$$E_{(\infty)} / E_d = (r / r_d)^2 \qquad (1.2)$$

where; E_∞: reverberation in the field of energy density
E_d: energy density
r_d : distance (m)

$$r_d = 1/4\sqrt{A/\pi} \qquad (1.3)$$

where; A: the total area of sound absorbing (m²)

Increasing the total absorption in the light of the results of these equations is important to ensure acoustic comfort and performance in internal spaces. For instance, if one assumes that there are no sound-absorbing elements in the space, the sound that a musical instrument produces can be considered rather disturbing; meaning that the sound becomes "readable" due to the sound absorbing elements within the space.

In this study, based on the calculations carried out related to the inner volume, total absorption will be increased to ensure acoustic comfort.

These calculations are needed in inner volumes where sound is the most important parameter, such as orchestral performances, events attended by many people, etc.

2.1.2. Reverberation at 500 Hz

An appropriate balance between direct sound and the reverberation sound field is to be identified. When equations (1.4) and (1.5) are combined:

$$RT = 0.161V / A \qquad (1.4)$$

$$E_{(\infty)} / E_{(d)} = (r / r_d)^2 \qquad (1.5)$$

$$E_{(\infty)} / E_{(d)} = 312r^2T / V \qquad (1.6)$$

When the same ratio needs to be provided and maintained in a hall or similar space, one can obtain RT (s) (Reverberation Time) using the R parameter.

$$RT = RV^{1/3} \qquad (1.7)$$

where; RT: reverberation time (s)
V : volume (m^3)
R : constant coefficients (s/m)

Table 1. Approximate values of $R=T/V^{1/3}$ [6]

Purpose	R [s/m]	Range of volume (m³)
Concert hall	0.07	1000-25000
Opera house	0.06	7000-20000
Cinema	0.05	up to 10000
Lecture hall	0.06	up to 4000
Recording studio	0.07	up to 1000

Table 1 shows the approximate R values for different volumes, based on functionality. Classical and Baroque music benefit from reverberation times of about 1.4 s, whereas 20th century orchestral music may require about 2.2 s of reverberation for the best effect. Another empirical equation that was derived at the end of a number of observations made in the best music halls: (S_T stands for the total area covered by the audience, orchestra and choir).

$$1/R_T = 0,1 + 5,4S_T / V \qquad (1.8)$$

where; S_T: total area (m^2)
V: volume (m^3)
R_T: reverberation time (s)

2.1.3. Warmth

Warmth is a comparative indicator between low- and medium-frequency reverberation times. RT/RT_{500} the desired values depend mainly on the type of music and speech. For instance, different values are needed for classical and baroque music.

Table 2. Acoustic environments of selected concert halls and opera houses [6].

	Hall	$V/10^3$ (m^3)	$S_T/10^3$ (m^2)	Reverberation Time (s) at Various Frequencies (Hz)						Delayed Arrival Time (ms)	Seats
				125	250	500	1000	2000	4000		
J	Jerusalem, Binyanei Ha'oomah	24.7	2.4	2.2	2.0	1.75	1.75	1.65	1.5	13–26	3100
N	New York, Carnegie Hall (before renovation)	24.3	2.0	1.8	1.8	1.8	1.6	1.6	1.4	16–23	2800
Bo	Boston, Symphony Hall	18.7	1.6	2.2	2.0	1.8	1.8	1.7	1.5	7–15	2600
A	Amsterdam, Concertgebouw	18.7	1.3	2.2	2.2	2.1	1.9	1.8	1.6	9–21	2200
Gl	Glasgow, St. Andrew's Hall	16.1	1.4	1.8	1.8	1.9	1.9	1.8	1.5	8–20	2100
P	Philadelphia, Academy of Music	15.7	1.7	1.4	1.7	1.45	1.35	1.25	1.15	10–19	3000
V	Vienna, Grosser Musikvereinsaal	15.0	1.1	2.4	2.2	2.1	2.0	1.9	1.6	9–12	1700
Bri	Bristol, Colston Hall	13.5	1.3	1.85	1.7	1.7	1.7	1.6	1.35	6–14	2200
Bru	Brussels, Palais des Beaux Arts	12.5	1.5	1.9	1.75	1.5	1.35	1.25	1.1	4–23	2200
Go	Gothenburg, Konserthus	11.9	1.0	1.9	1.7	1.7	1.7	1.55	1.45	22–33	1400
L	Leipzig, Neues Gewandhaus	10.6	1.0	1.5	1.6	1.55	1.55	1.35	1.2	6–8	1600
Ba	Basel, Stadt-Casino	10.5	0.9	2.2	2.0	1.8	1.6	1.5	1.4	6–16	1400
C	Cambridge, Mass., Kresge Auditorium	10.0	1.0	1.65	1.55	1.5	1.45	1.35	1.25	10–15	1200
(Bu)	Buenos Aires, Teatro Colon	20.6	2.1	—	—	1.7	—	—	—	13–19	2800
(NM)	New York, Metropolitan Opera	19.5	2.6	1.8	1.5	1.3	1.1	1.0	0.9	18–22	2800
(M)	Milan, Teatro alla Scala	11.2	1.6	1.5	1.4	1.3	1.2	1.0	0.9	12–15	2500

Source: Adapted from Beranek, *op. cit.*

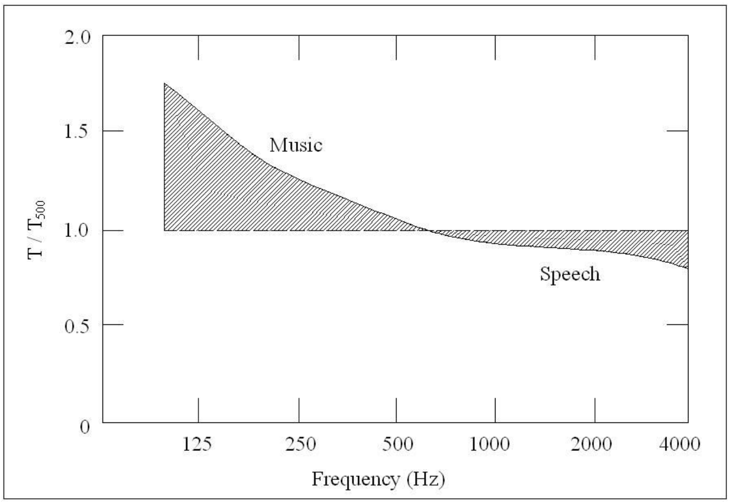

Figure 1. Relative reverberation-time limits for music and speech.

2.1.4. Intimacy

It is of utmost importance that the sound not be disturbing. This criterion is especially important in concert halls, opera houses and conference halls, and depends on the sound coming directly from the source and the reverberation right after that.

2.2. Parameters Depending on Early Reverberations

2.2.1. Initial Time Delay Gap [ITDG]

This parameter can be defined as the time difference between the sound coming directly from the source and reverberation sound. In other words, it is the same as intimacy.

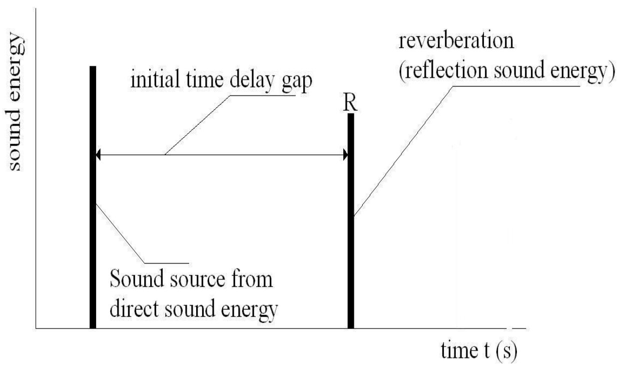

Figure 2. A reflection pattern graph, the initial time-delay gap

2.2.2. Texture

Previous studies have shown that the early reverberation reaches the human ear generally in the first 80 ms. At the beginning of these early reverberations, it can be seen that a high number of monotonous reverberations is related to a good texture.

2.2.3. Interaural Cross Correlation Coefficient [IACC]

In the research carried out of audiences have revealed that sound is perceived to arrive at either ear at different times. Relevant tests are generally carried out at six-octave intervals (125–4000 Hz). Within IACC ±1 ms, the cross-correlation function defines the maximum value. The differences regarding IACC3; these three octaves central frequency values are IACC user average for the 500, 1000 and 2000 Hz frequency bands. IACC3 has two components;

IACCE3: early component, 0–80 ms,
IACCL3: late component, 80–750 ms. [1,5].

2.3. Parameters Depending on Acoustic Energy

2.3.1. Clarity C80, C50 [dB]

Clarity refers to the comparison of the early sound energy ratio occurring within a volume with reverberating sound, and is expressed in dB. It is defined as the distance between sounds in the inner space. If the clarity is very low, the human ear cannot distinguish the pace of the individual pieces in the music. The functionality of both parameters is important for both architectural and stage design. The relationship between reverberation and clarity is quite clear: clarity will be higher in an anechoic room due to the lack of reverberation. On the other hand, in churches, for example, high reverberation will result in a poor perception of music (C80 may be negative). The approximate values for C80 are as follows:
Although orchestral music is in the (0 dB)–(-4 dB) interval, many conductors work in the C80 (1 dB)–(5 dB) interval so that they can hear all the details. For musicians, the (1 dB)–(5 dB) interval is mostly sufficient, but on the other hand, for conferences and presentation halls clarity should be measured using C50.

2.3.2. Stage Support

This parameter does not affect the audience in a performance hall, but is of utmost importance for the artists and musicians on stage. The sound reaching the artists and musicians from the reflecting surfaces on the stage is a function of the acoustic power of the orchestra, and is defined as the sound energy ratio in the first 10 ms and sound energy between 20 and 100 ms.

3. GEOMETRY

From antiquity onwards, function and user requirements have always played an important role in the historical development of the volumetric features of theatre buildings, concert halls and opera houses; and "acoustics" also has been an important characteristic of these types of structures. The geometry of the architectural plans of theatres, concert halls or opera houses can be categorized under four types based on current practices, all of which have a direct impact on acoustics:

1) Rectangular plan
2) *Horseshoe plan*
3) Fan-Shaped plan
4) *Vineyard plan*

In inner spaces where sound is an important feature, the basic acoustic parameter is the reverberation time. Studies carried out to compare the theoretical and empirical values obtained from the plan metric features mentioned above revealed that the reverberation time of the "horseshoe plan type" is low, while the theoretical reverberation time obtained from "rectangular or fan-shaped plan types" is compatible with the values obtained from acoustic measurements. These measurements were carried out in closed volumes that were designed to accommodate 1,000 people.

3.1. Rectangular Plan

The parallel walls in a rectangular plan scheme may result in a corridor-like effect, and these parallel surfaces within the volume may result in changes in reverberation times and acoustic problems in standing waves.

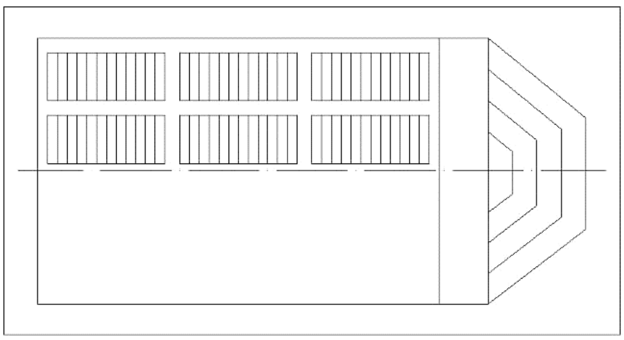

Figure 3 - Rectangular plan.

3.2. Horseshoe Plan

This plan scheme provides good visibility and mutual eye contact between the sound source and audience, and promotes a feeling of intimacy. This form of interior design can prevent problems with acoustics, can provide a correct reverberation time and can ensure the homogeneity of the direct sound. If more absorbing elements than needed are used in the inner space, the reverberation time may be lower than envisaged.

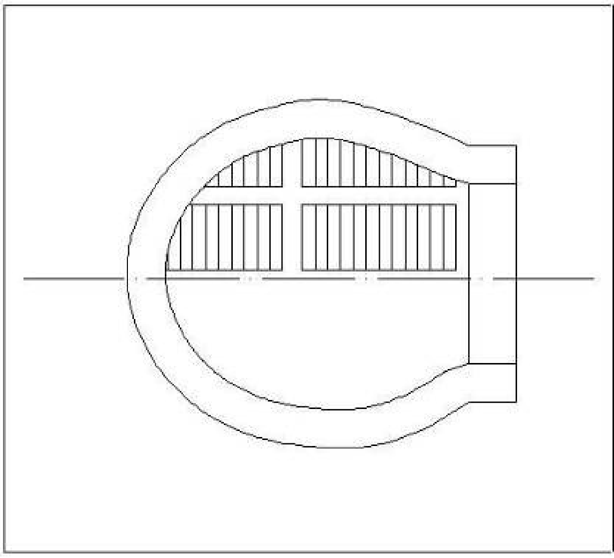

Figure 4 - Horseshoe plan.

3.3. Fan-Shaped Plan

The Fan-Shaped Plan scheme provides not only good visibility and acoustics, but also makes the stage structure suitable for a wider audience. Although sound reflecting from the rear surfaces reaches the front with some delay, the side surfaces hinder echo formation due to the shape of the hall. This situation can be further improved using sound absorbing or reflecting elements on the back surfaces.

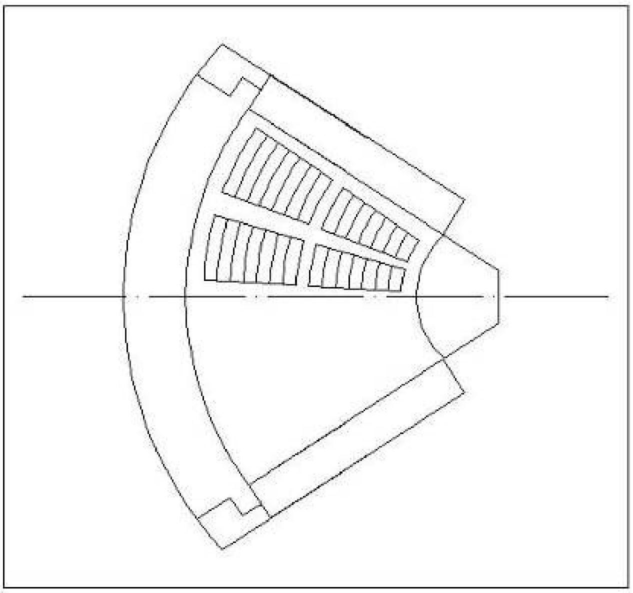

Figure 5 - Fan-shaped plan.

3.4. *Vineyard Plan*

The Vineyard Plan Type first appeared in the 20th century as an important geometrical configuration to be used in concert halls, theatre buildings, etc. This plan scheme provides a spacious hall in which the stage is surrounded by the audience. This also bolsters the legibility and the clarity of the sound between the performer and the audience. Another major advantage that the vineyard plan type provides for designers is that any regional amendments that need to be carried out within the internal volume do not affect the whole hall.

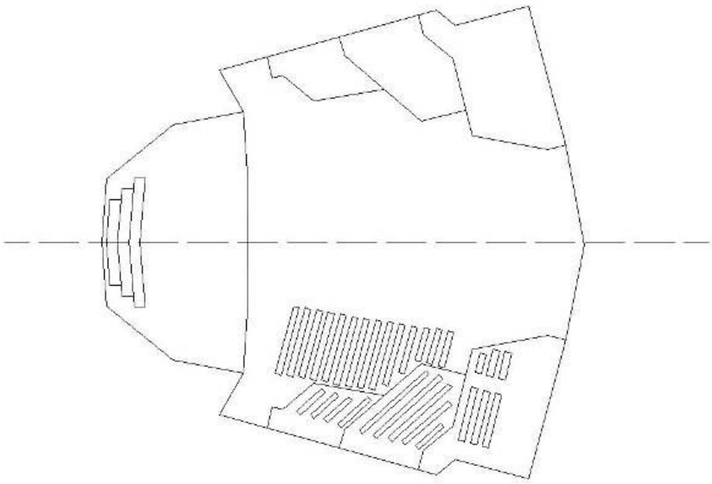

Figure 6 - Vineyard plan.

4. VOLUME

In internal volumes where sound is an important component, acoustic energy density will decrease as the distance in which the sound can propagate increases. In this case, secondary support is needed within the volume, and speakers should be used on any necessary internal surfaces. Table 3 shows the various volume sizes in which the sound source can be sufficient.

Table 3. Sound source of power may be adequate in volumes size

Sound Source	Volume (m^3)
The average speaker	3000
Professional speaker	6000
Instrumental/Vocal	10000
Large symphony orchestrar	20000
Large choir	50000

The Heyl equation that is in common use for calculating the optimum ratio between the volume (V [m³]) and musician and orchestra (n) is as follows:

$$V = 250n - 1340 \tag{1.9}$$

where; V: volume (m^3)
n : The number of musicians in the orchestra (people)

5. RESULT and DISCUSSION

The main aim of acoustic design in theatre buildings, concert halls and opera houses is to help the sound propagating from a source to be homogeneously distributed within the internal volume and reach the entire audience. Sound level decreases as one moves away from the source, meaning that halls should be no larger than a certain size. One of the most important criteria to be taken into account during interior design is the maintenance of visual contact between the audience and the stage. The design process starts with a scheme that can accommodate at least 100 people; then, while gradually increasing this number, the stepped seating plan, and its orientation and position in reference to the stage should be designed. The other criterion for evaluation of the reverberation time; Sabine's equation is based on dissipation of acoustic energy after the sound source has been turned off. The reverberation time elongates with growing volume and diminishes with the total area of surface of the auditorium and with the absorptive. The reverberation time should be selected as optimum, in conformity with the function of the interior volume.

Clarity should be ensured within the internal space. In halls in which speaking is the main function to be performed, direct sound is more desirable, while concert halls and opera houses require a longer reverberation time, as a more vivid and richer sound is desired.

In parallel with the development of concert hall geometry, today, the acoustic design and the development of suitable acoustic parameters has gained speed, during which it has become apparent that the Vineyard Plan scheme offers particular advantages in terms of acoustic design and hall geometry. This plan type has a dynamic, variable structure, in which the inner space is set out in terraces (vineyard), allowing a variety of different activities. The acoustic data obtained from halls used for different purposes appear to attain the desired levels. The other important design criteria can be any mechanically moving of the vineyard part. The aim here is to ensure replacement of the reverberation time.

Reverberation time is the most important parameter, describing hall's acoustic, it does not tell everything. Any two halls with the same reverberation time can sound totally different. Thus, room acoustic parameters are introduced. They are separated into three main groups those in connection with reverberation time, early reflections or acoustic energy.
When these structures are examined from an architectural/interior design perspective, one can conclude that all works that need to be done within such spaces should be carried out as a team effort, and that it is paramount that acoustic design and planning be conducted by relevant experts.

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