ACOUSTICAL CHARACTERISTICS OF HISTORICAL TURKISH BATHS

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ABSTRACT

ACOUSTICAL CHARACTERISTICS OF HISTORICAL TURKISH BATHS

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Comprehensive studies are needed to better understand the original acoustical features of historical baths in order to uncover the historical technologies that enabled the acoustical performance for which they are renowned and to ensure they retain this performance with time. In this study, acoustic performances of Şengül Hamamı and Kadı Hamamı, two 15^{th} century historical baths belonging to the Ottoman period, were examined to discover their original acoustical features and to assess their present situation by taking into consideration the recent incompatible repair work. The analyses were done by using 3D computer modeling and acoustical simulation methods supported by laboratory analyses. The results were evaluated in terms of sound absorption characteristics of historical lime-based plasters, the original acoustical features of historical Turkish baths and acoustical failures related to recent repairs. The study showed that these baths had originally well-designed acoustical features provide for a proper environment for musical performances. This success was attributed to the conscious use of historical materials having high sound absorption characteristics. It was seen that these original acoustical features had been destroyed by wrong repairs using cement-based plasters. These plasters demonstrated incompatible acoustical properties, such as less porosity and lower sound absorption coefficients. This study also helped to define acoustical specifications for such historical baths to be maintained in restoration work.

Keywords: Historical Turkish baths; historical lime plasters, acoustical simulation; acoustical parameters, sound absorption coefficient.

ÖZ

TARİHİ TÜRK HAMAMLARININ AKUSTİK ÖZELLİKLERİ

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Tarihi Türk hamamlarının kendine özgü akustik niteliklerini keşfetmek ve işlevlerinin uzun yıllar boyu devamını sağlamak için kapsamlı araştırmalara ihtiyaç vardır. Bu çalışma kapsamında, 15.yy Osmanlı dönemi yapısı olan Kadı Hamamı (Diyarbakır) ve Şengül Hamamı'nın (Ankara) özgün akustik özellikleri ve onarımlar sonucu ortaya çıkan akustik sorunları incelenmiştir. Çalışmalar, bilgisayar ortamında yapılan üç boyutlu modelleme ve akustik benzetim (simülasyon) teknikleri kullanılarak yapılmış ve laboratuvar analizleri ile desteklenmiştir. Sonuçlar, "tarihi Türk hamamlarına özgü tarihi kireç sıvalarının ses yutma özellikleri", "hamamların özgün akustik niteliklerinin tanımlanması" ve "yanlış onarımların özgün akustik niteliklerine olan olumsuz etkileri" açılarından değerlendirilmiştir.

Hamam yapılarının, müzikal etkinlikleri bakımından özgününde iyi tasarlanmış akustik niteliklere sahip olduğu anlaşılmıştır. Bu başarıda, tarihi yapı malzemelerin bilinçli kullanımı önemli rol oynamaktadır. Tarihi hamam yapılarında ses yutma kapasitesi yüksek olan tarihi kireç sıvaların kullanılmıştır. Tarihi sıvalarınkine göre ses yutma özellikleri çok düşük olan çimento sıvaları, akustik açıdan tarihi Türk hamamlarının onarımlarında kullanılmamalıdır. Bu malzemeler ile yapılan onarımlar sonucunda tarihi hamam yapıları, özgününde sahip oldukları iyi tasarlanmış özgün akustik niteliklerini tamamen kaybetmişlerdir. Aynı zamanda bu çalışma, tarihi malzemelerle uyumlu onarım malzemelerinin akustik niteliklerini tanımlanmasına yardımcı olmuştur.

Anahtar Kelimeler: Tarihi Türk hamamları, tarihi kireç sıvası, akustik benzetim, akustik parametreler, ses yutma katsayısı.

To

my parents,

Nazlı and Şirin Aydın,

for their

lasting support and love.

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Lastly, as to her parents, when she fell down on her knees, they treated her wounds and tears with tenderness. She knows she can never thank them enough by any amount of word for their endless love, sacrifices, continuous support and patience.

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CHAPTER 1

INTRODUCTION

In this chapter is first presented the argument for and the objectives of the study. It continues with the section entitled “procedure”’ where a succinct account of the basic steps followed and its conduct is outlined and concludes with a preview of what is encompassed in subsequent chapters under the section titled, disposition”.

1.1 Argument

Historical Turkish baths are the fundamental documents representing the continuous experience of bathing culture in Anatolia and keeping architectural and building technologies achieved in the past. The historical technologies should be well-understood in order to discover the builders’ knowledge of the past related to the building materials, functional systems such as heating, ventilation, water supply and drainage systems and building acoustics, establishing a well-functioning structure. This knowledge on historical technologies is also essential for the maintenance and conservation of historical Turkish baths in order to keep their proper functioning and original features for long periods of time.

This study was focused on the assessment of acoustical performance of historical Turkish baths with an emphasis on their original acoustical features and the present acoustical situation by taking into account the recent repairs. There is, in fact, lack of knowledge in the literature on the definition of original acoustical environment of historical Turkish baths in terms of basic acoustical parameters. The number of studies on the analyses of original acoustical properties of historical baths, considering acousto-physical characteristics of historical materials and microclimatic conditions particular for bath structures, such as very hot and wet air, remains rather limited. Comprehensive studies are, therefore, needed, in this regard.

It was known that the acoustical performances of buildings have been taken into consideration since ancient times, such as Greeks and Romans. For instance, the ancient amphitheatres, such as Aphrodisias amphithetre (Aydın) and Aspendos theatre (Antalya), had well-designed acoustical environment for musical and speech activities (Ciechomski, Ulicny, Cetre and Thalmann, 2004; Gade, Lisa, Christensen and Rindel, 2004), Sokullu (İstanbul) and and also Süleymaniye (İstanbul) mosque and Saint Irene Byzantine church (İstanbul) (Weitze, Christensen, Rindel, Gade, 2001). The knowledge on building acoustics can not be limited only to the acoustical design of open spaces, such as amphitheatres. Historical structures, such as Ottoman baths, should have particular acoustical features as the part of their architectural and functional design, which should have been achieved by the materials and construction technologies of their period. Here, this research was conducted to find out the knowledge on historical material properties contributing to the acoustical features of historical Turkish baths.

The use of three-dimensional (3-D) acoustical simulation methods together with computer modeling software has a vital importance for the assessment of acoustical features of historical structures since they allow an opportunity to make a detailed examination in terms of different parameters. While, there are some studies on the acoustical assessment of historic structures in the literature (Ciechomski, Ulicny, Cetre and Thalmann, 2004; Gade, Lisa, Christensen and Rindel, 2004), a conscious use of these simulation methods is essential in order to achieve reliable data and to develop these methods for the acoustical assessment of historical structures. The accuracy of the analyses done by simulation methods is dependent on the accuracy of the input in terms of real sound absorption coefficient values of materials, geometrical definition of spaces and real microclimatic conditions of spaces. However, there is the lack of knowledge on the acousto-physical properties of historic materials such as historic brick, historic mortar and lime-based plasters. There is, therefore, necessity of making research on the determination of sound absorption characteristics of historical materials.

Considering all above the study was shaped to discover the original acoustical characteristics of some historical baths by using 3-D computer modeling and acoustical simulation methods. For this purpose two historical Turkish baths belonging to the 15th century, Şengül Hamamı and Kadı Hamamı, still representing the continuous experience of Turkish bathing culture in Anatolia were examined in the study. Knowledge about the sound absorption properties of historical materials was important to better understand the historical materials technology related to acoustics of historical baths and to achieve accurate data to define the original acoustical environment of these structures by means of 3-D acoustical simulations. In this regard, the sound absorption properties of historical materials, such as lime-based interior plasters, were also examined in the study.

1.2 Objectives

This study was conducted to discover the original acoustical performance of historical Turkish baths and acoustical properties of historical materials contributing to their performance. This knowledge was essential to better understand the technologies of historical architecture and materials contributing to the acoustical features of historical Turkish baths and to keep these inherent technological features for the future by means of well-planned conservation programs. The present acoustical performance of the historical Turkish baths was also examined in relation to the use of improper repair materials.

In the light of these concerns, the specific objectives of the study were:-

1. to define the original acoustical features of historical Turkish baths in terms of basic acoustical parameters and to determine the sound absorption characteristics of historic finishing materials at interiors, such as lime-based interior plasters.

2. to evaluate the present state of acoustical performance for historical Turkish baths by taking into account the acoustical failures occurred in time and use of improper materials in recent repairs, such as cement-based plasters.

3. to improve the use of computer-based acoustical simulation methods for the analyses of historical structures with an emphasis on sound absorption characteristics of historic materials, climatic conditions particular to Turkish baths and their geometrical features.

4. to define the acoustical specifications for the historical Turkish baths and the historical materials used in these structures, contributing to the conscious approach for the repairs of Turkish baths and selection of proper materials.

The two typical historical Turkish baths, Şengül Hamamı and Kadı Hamamı, were examined to achieve knowledge based on these objectives.

1.3 Procedure

This study was conducted in four phases. The first consisted of literature survey conducted on the architectural features of the historical Turkish baths in Ottoman Period, general definitions of acoustics and its parameters, criteria affecting the acoustical features of historical baths, use of 3-D computer modeling and acoustical simulation methods for the analyses.

In the second, two historical Turkish baths belonging to Otooman period were selected for the acoustical analyses. The first one is Şengül Hamamı which is in the province of Ankara and the second one is Kadı Hamamı which is in the province of Diyarbakır. The measured drawings of these structures were taken from General Directorate of Foundations and then used for their 3-D modeling and acoustical simulation.

In the third, case studies were prepared for the acoustical computer simulation program and this part was described in the following chapter “material and method”.

After collecting all related documents, whole information was analysed to explore the differences and similarities between past and present conditions of Turkish baths. All cases were analyzed in the same predetermined parameters so that we could compare them easily. Thereafter, whole analysis results were combined in comparison charts. In the light of findings, the author gave some recommendations for future studies.

1.4 Disposition

The study was presented in five chapters. In this chapter, an introduction to acoustics and historical Turkish baths was made, and the scope and objective of the study were explained.

In the second chapter, an overall literature survey was carried out. Developments and researches made in the history of Turkish baths were reviewed. A short summary on general concepts of acoustics was presented in the second chapter, by the help of those definitions, relations between Turkish baths and acoustics concepts were explained.

The third chapter was mainly about the analysis methods and their usage in retrieving the data about the Turkish baths to be interested in. In the first phase, the architectural, structural and acoustical information about two Ottoman Turkish baths were given. History, size, volume, shape, plans, sections, elevations and other design features of Turkish baths were presented and their correlations with the acoustical parameters were underlined.

The fourth chapter was mainly about the modeling process which was described and the Odeon acoustics software was underlined. In the fourth chapter, five acoustical parameters which are reverberation time (RT), early decay time (EDT), clarity (C80), lateral fraction (LF), and speech transmission index (STI) were studied for each Turkish bath. Results of the computer simulations and calculations were presented in figures and tables.

In the fifth chapter, discussion of the results and conclusion were presented. Results obtained from software were evaluated, discussed and compared in terms of appropriation of the acoustical parameters for past conditions and present conditions and also repair condition of the Turkish baths in terms of acoustical parameters. This chapter ended with conclusion, in which the findings of the study were summarized and recommendations were offered for future studies.

CHAPTER 2

THE LITERATURE SURVEY

In this chapter, the literature survey about historical Turkish baths, their architectural features, basic acoustical parameters and studies on 3-D acoustical simulation of historical structures are presented. This is studied basically under four main topics: Firstly, general information on the architectural features of historical Turkish baths in Ottoman period was given. Secondly, acoustical parameters for the analyses are explained by taking into consideration the reverberation time, early decay time, lateral fraction, clarity and speech transmission index. Thirdly, criteria affecting the acoustical features of historical baths are described in terms of microclimate features, geometry evaluation, and acoustical properties of materials. At the final part 3-D computer modeling and acoustical simulation analyses are described regarding their calculation methods for acoustical analyses.

2.1 Historical Turkish Baths in the Ottoman Period

Baths are buildings which are used by people for collectively washing. "*Hamma*" in Arabic means to heat; "*Hamam*" in Hebrew means to be hot (Taşçığlu, 1998). Today the word "*hamam*" in Turkish means a place where one washes or bathes. In the past, people were always in need of washing due to health, cleanliness or religious reasons. People, therefore, were in need of special spaces, which were called "bath structures" or "*hamam*"s for bathing in water.

The literature survey related with historical Turkish baths in Turkey showed that the first publication done by Heinrich Wilde (1909) contains the description of Bursa and its monuments including Turkish baths and kaplıcas. It gives the definition of Turkish baths and their sections. Later in 1922 H. Glück edited "Die Bader Constantinople's" studied on the Istanbul Turkish baths. Later, Karl Klinghardt (1927) documented some information about historical Turkish baths in his research "Türkische Bader". From that time, some of the local researchers studied the architectural features and typologies of historical Turkish baths (Akok, 1968; Albayrak, 1997; Alp, 1964; Arseven, 1965; Aru, 1949; Ataman, 1997; Semavi, 1960; Tascıoglu, 1998; Tuna, 1987).

Taşçıoğlu (1998) states that Turkish water architecture started to develop with the Seljuk. Function of the Moslem religion, for development of baths, was absolutely important, because cleanliness was one of its necessities. Buildings had been done parallel to it, because the Moslem religion had determined the style of bathing. Pools which can be seen in the Roman baths can not be seen in Turkish baths except in thermal baths (kaplıcas). The reason is that Moslem religion does not permit bathing in the water which is not flowing. The Turks arranged such characteristics of inner architecture according to their religious rules.

Tuna (1987) says that plan types of social baths and thermal baths are architecturally similar. Generally, these Turkish baths belonging to Ottoman period consist of four sections (Figure 2.1.). They were given below:
1.Soyunmalık /Camegah (undressing room/ the Apodyterium)
2.Ilıklık (the Tepidarium – the warm space)
3.Sıcaklık (the Caldarium – the hot space)
4.Külhan (the furnace)

The apodyterium (soyunmalık) is often in a quadrangular or rectangular form. This section means undressing room. The tepiderium (ılıklık) is the first section of a Turkish bath before entering the bathing area. It is a resting and refreshing area and it is warm. The tepiderium (ılıklık) is an area between the cool apodyterium and the hot caldarium (sıcaklık) so that the body temperature can adapt itself to the difference in heat. The Tepiderium (ılıklık) is the first section of a Turkish bath before entering the bathing area. It is a resting and refreshing area and is warm. The tepiderium (ılıklık) is an area between the cool apodyterium and the hot caldarium (sıcaklık) so that the body temperature can adapt itself to the difference in heat. The Tepiderium (ılıklık) is a large area covered with either domes or vaults (Taşçıoğlu, 1998).

The caldarium (sıcaklık) is the hottest area of the Turkish bath. On top of the domes there are glass fanus over the light holes in the cupola called elephants' eyes that bring in the light during the day and give out a decorative light during the evening(Aru, 1949). Under the big dome, in the centre of the caldarium-sıcaklık, there is the göbektası. This marble slab is elevated from the floor by 45-50cm and is often in the shape of an octagon or very rarely a circle. This is the hottest section of the building where the bathers lie down or sit. Four eyvans plans were brought from Central Asia by the Turks and later developed by the Seljuk and Ottomans (Taşçıoğlu, 1998).

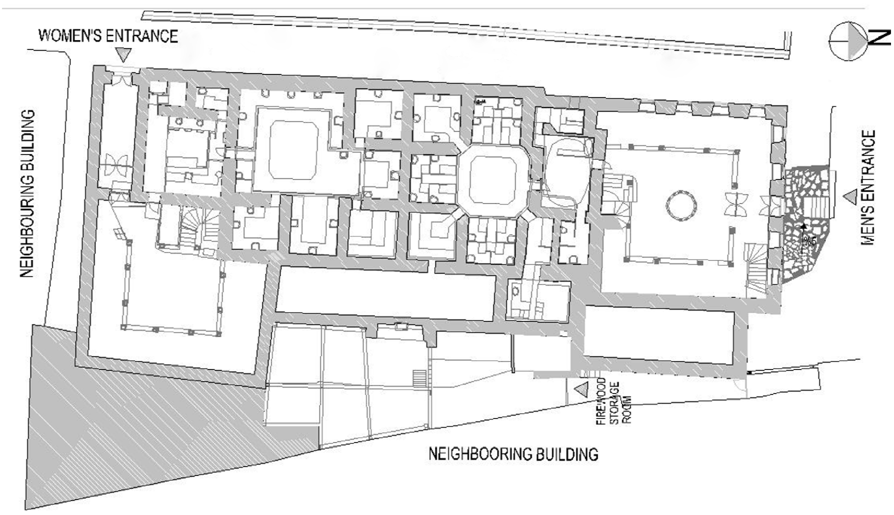


Figure 2.1 Plan of Şengül Hamamı

Source : Archives of the General Directorate of Pious Foundations, 2008

2.2 Acoustical Parameters for the Analyses

Room acoustics is the science of radiation, propagation and transmission of sound waves within the enclosed space. Generally, it refers to the characteristics of auditoriums, theatres and studios with respect to their design. Room acoustics is an objective phenomenon, and consists of several qualitative and quantitative parameters necessary to be understood. Barron(1998), describes the objective parameters as; reverberation time, early decay time, early-to-late sound index, early lateral energy fraction and total sound level. Fullness of tone, definition of clarity, fullness and definition, intimacy, timbre, tone colour and brilliance are stated as parameters of subjective.

2.2.1 Reverberation Time (RT)

The reverberant sound in a room dies away with time as the sound energy is absorbed by multiple interactions with the surfaces of the room. In a more reflective room, it will take longer for the sound to die away and the room is said to be “live”. In a very absorbent room, the sound will die away quickly and the room will be described as acoustically “dead”. But the time for reverberation to completely die away will depend upon how loud the sound was to begin with, and will also depend upon the acuity of the hearing of the observer. In order to provide a reproducible parameter, a standard reverberation time has been defined as the time for the sound to die away to a level 60 decibels below its original level (Figure 2.2). The reverberation time can be used to make calculation (Nave, Nave, 1985).

The sketches (Figures 2.2 - 2.4) depict the sound received by a single listener as a function of time as a result of a sharp sound pulse some distance away. The direct sound received is followed by distinct reflected sounds and then a collection of many reflected sounds which blend and overlap into what is called reverberation. The delay between the direct sound and the early reflected sound (Figures 2.3) is a significant characteristic for an auditorium, though not as important as the overall reverberation time (Nave, Nave, 1985). Although the reverberation time is defined as the time it takes for the sound to decay 60dB, this is seldom possible to measure due to the unavoidable background noise. Further, the initial part of the reverberation decay is usually the most interesting part. The reverberation time is therefore normally based on the decay rate for a range of 20dB or 30dB starting 5dB below the stationary level (Norsonic, 2008). The value is afterwards extrapolated to 60dB assuming that the part of the decay that we used is representative for the entire decay. It is common practice to specify the range used as "T_{20}", "T_{30}", *etc.*, all having the same numeric value if the decay is linear.

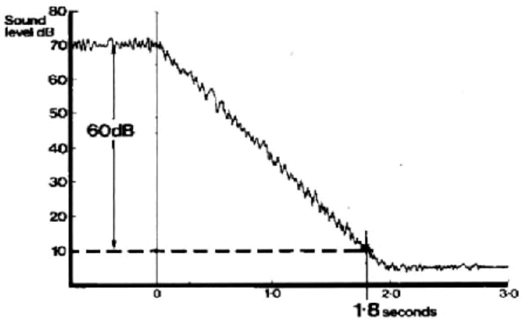


Figure 2.2 RT definition with sound decay.
Source: www.hyperphysics.phy-astr.gsu.edu/hbase/acoustic/arcaco.com, 2008

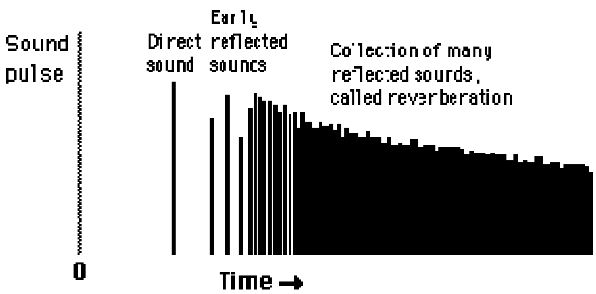


Figure 2.3 Sound received by a single listener as a function of time.

Source: www.hyperphysics.phy-astr.gsu.edu/hbase/acoustic/arcaco.com, 2008

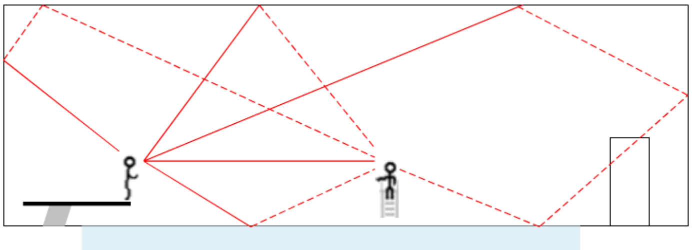


Figure 2.4 Illustration showing the reflection of the sound wave perceived by receiver.

Source : Archives of the Ecophon group, 2008

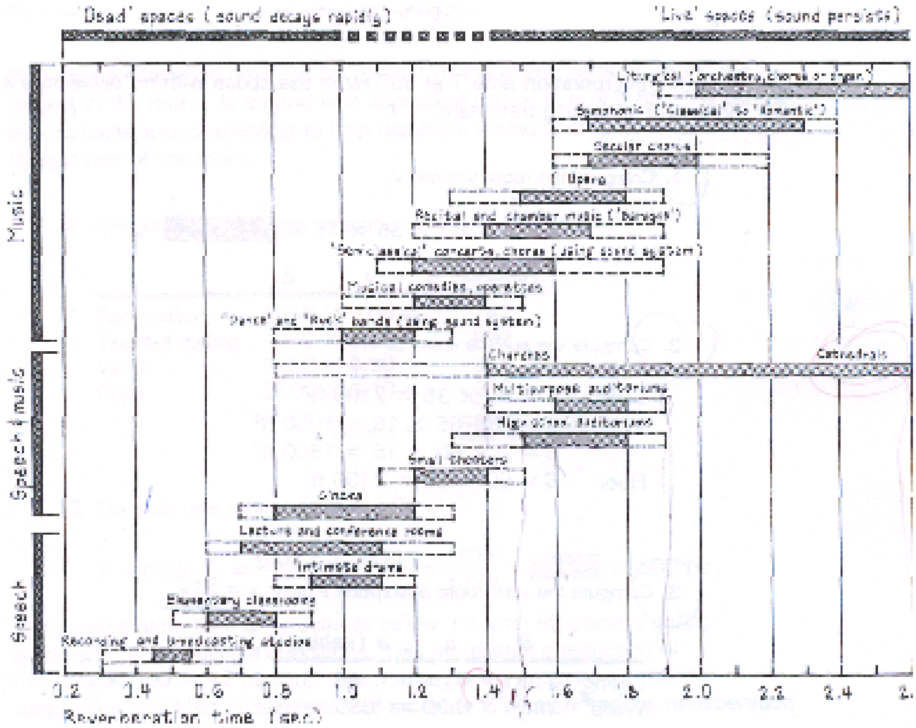


Figure 2.5 Optimum RT values for various occupied facilities.
Source: Egan., 1988, pp.64

Optimum RT is the preferred ranges of reverberation time at mid-frequency (average of reverberation at 500 and 1000 Hz) for a variety of activities; optimum RT values are given on the bar graph (Figure 2.5). In the graph, the ranges, based on the experience of normal-hearing listeners in completed spaces, are extended by dashed sections at the ends of the bars to indicate the extreme limits of acceptability. Satisfactory listening conditions can be achieved in auditoriums which have different reverberation times within the preferred range, provided other important acoustical needs are fulfilled (Egan, 1988). In general, large rooms should be nearer to the upper end of the RT ranges than smaller rooms of the same type (Figure 2.5). Therefore, liturgical organ music is composed for church or cathedral sized rooms, while chamber music is intended for small rooms. The optimum RT (Table 2.1 and Figure 2.5) for an auditorium or room, of course, depends upon its intended use. Optimum RT of about 2 seconds is desirable for a medium-sized, general purpose auditorium that is to be used for both speech and music. Optimum RT for a classroom should be much shorter, less than a second. A recording studio should minimize reverberation time in most cases for clarity of recording. (Egan, 1988).

Table 2.1 Recommended occupied reverberation times for an auditorium.

Reverberation time RT	seconds
Organ music	>2.5
Romantic classical music	1.8-2.2
Early classical music	1.6-1.8
Opera	1.3-1.8
Chamber music	1.4-1.7
Drama theatre	0.7-1.0

Source: Barron, 1993, pp.29

Barron (1993) suggests that the appropriate RT for an auditorium should be determined principally on the basis of program (Table 2.1). Many references are found in the literature to optimum the RT also being a function of hall volume. A major dilemma exists for RT design for multi purpose spaces. With orchestral music requiring a 2s RT and speech only 1s, use of single space for both speech and music is usually not possible without electronic assistance. Selecting a compromise time for such a situation can result in acoustics which are neither able to support intelligible speech nor are sufficiently live by musical standards. If a single figure is quoted for the RT, it generally refers to the mid-frequency value, averaged between 500 and 1000 Hz (Figure 2.6). At high frequency above 1 kHz, the RT inevitably decreases due to air absorption.

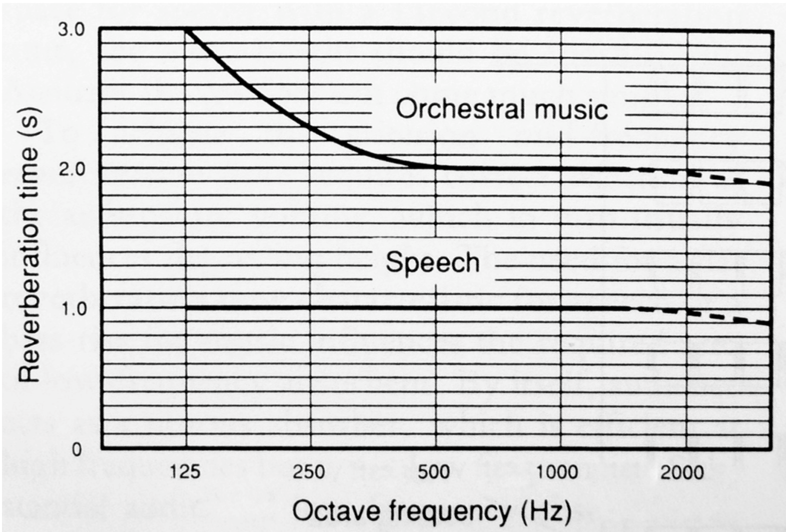


Figure 2.6 General recommended reverberation frequency characteristics for speech and orchestral music use.
Source: Barron, 1993, pp.29

The human brain processes sound in such a way that, if the difference in the arrival time between two separate, similar sounds is any greater than 0.05 (1/20) s, two distinct sounds are heard. If the difference in arrival time is less than 0.05 s, only one sound is heard. This phenomenon is known as an echo (Cowan, 1994).

2.2.2 Early Decay Time (EDT)

Reverberation time is the time required for the reverberant sound to decay 60dB below the maximum whereas early decay time is the RT calculated from the initial portion of the room decay curve. Formally the EDT is the time taken for the first 10 dB of level reduction multiplied by 6, making it comparable to the RT. EDT varies less with occupancy than does the RT and is measured without an audience (Long, 2006).

Barron (1998) claims that the subjective sense of reverberation, for concert halls, is best related to the EDT, and one finds in these directed designs that the EDT is often shorter than the RT. If the RT happens to be somewhat short, the sense of reverberation can then become subjectively inadequate. The only solution appears to be extending the RT, in order to leave an EDT which is long enough, even if the RT becomes longer than the recommended maximum of 2.2s. Interpretation of the EDT is firstly as an absolute value for occupied conditions relative to a criteria range of perhaps 1.8-2.2 seconds (the conversion from unoccupied to occupy can be made according to the ratio of RT.). But secondly, the agreement or not between EDT and RT is an indication of diffuseness or directness of the design. For measurements in a highly diffuse space, the agreement is very good, whereas in a hall in which a lot of early reflections are directed at the audience, the EDT is found to be significantly shorter than RT.

2.2.3 Lateral Fraction (LF80)

Lateral (energy) fraction, in other words, objective envelopment is the ratio of the integrated sound energy in the first 80msec after the direct sound measured from the sides of the listener's head compared to the total integrated energy level of the early sound at the same location (Long, 2006).

The lateral energy fraction is supposed to be related with a sense of spatial impression with higher values of LF80 providing a greater sense of spatial impression. The sense of spatial impression was first reported by Marshall (1967) who described it as spatial responsiveness, where the opposite was expressed by the manager of the Concertgebouw orchestra of Amsterdam as the "feeling of looking at the music". Baron investigated this effect further and concluded that early reflections up to 80 ms were perceived differently than reverberation. He conducted subjective tests using a single side reflection and evaluated the effects of tone coloration, echo disturbances, and spatial impression. The largest effects were found in differences of spatial impression and Baron coined the term in this paper. Barron and Marshall continued to pursue this topic and found subjective differences in sensations from sounds at different frequencies. Lower frequencies tended to give more about an impression of being surrounded by the sound. The upper limit of 80 ms for early reflections was confirmed in this work and the objective measure of lateral fraction was defined. They also determined that spatial impression is a function of reflection angle (Long, 2006). Preferable ranges of LF80 are 0.1 to 0.3 for halls (Barron, 2000; Marshall, Barron, 2001).

2.2.4 Clarity (C80)

C80 is the degree to which every detail of the performance can be perceived. While the richness and fullness added by auditorium reverberation are desirable, such reverberation decreases clarity of articulation. So fullness and richness work against C80, and a reasonable RT must be reached by an appropriate compromise of clarity fullness. If there is no reverberation in a dead room, the music will be very clear and C80 will have a large positive value. If the reverberation is large, the music will be unclear and C80 will have a relatively high negative value. C80 becomes 0 dB, if the early and the reverberant sounds are equal. If the C80 is too low, the fast sections of the music are not "readable" anymore. (Long, 2006; Nave, Nave, 1985). Values of C80, which can range from small positive numbers to small negative values, are for very fall into the ±4 dB range, for concert halls. The preferred values of C80 are between 0 and -4 dB (Long, 2006).

2.2.5 Speech Transmission Index (STI)

The Speech Transmission Index (STI) is used for predicting speech intelligibility through impulse response. Speech intelligibility measures how much spoken information can be understood in a particular environment. It is affected by reverberation time, background noise level or rather the signal to noise ratio (S/N), room volume and geometry together with the placing of sound absorbing, sound reflecting and sound scattering surfaces. The shorter RT is better for the intelligibility of speech, until the background noise begins to dominate (Figure 2.7). Speech intelligibility is a direct measure of the fraction of words or sentences understood by a listener (Barron, 1993; Long, 2006; Kuttruff, 2000).

For most application if we can grasp more than 85-90% of the words being spoken we achieve very well comprehension-virtually 100% of the sentences. With an understanding of more than 60% the words we can still get 90% of the sentences and that is quite good. If we understand less than 60% of the words the intelligibility drops off rapidly. This is not surprising since the brain is impressive computers which can select useful information and fill in the gaps between the words we understand (Long, 2006).

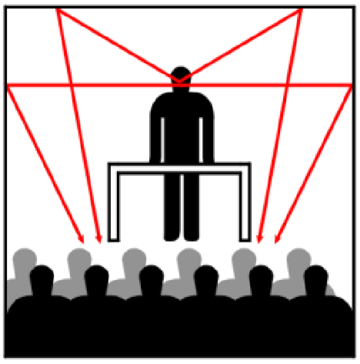


Figure 2.7 The figure showing in a room with a long reverberation time, one word does not have time to decay before the next reaches the listener, so the intelligibility of speech is poor.

Source : Archives of the Ecophon group, 2008

The articulation index (AI) is a detailed method of measuring and calculating speech intelligibility (French and Steinberg, 1947). The result of an AI calculation is a numerical, which ranges from 0 to 1, with 1 being 100% word or sentence comprehension. Beranek (1947) suggests that a listening environment with an AI of less than 0.3 will be found to be unsatisfactory or marginally satisfactory, while an AI values between 0.3 with 0.5 will generally be acceptable. For AI values of 0.5 to 0.7 intelligibility will be good, and above 0.7 intelligibility will be very good to excellent. Table 2.2 shows the intelligibility rating and relations among STI values.

It is noted that, human speech involves a wide range of frequencies, from bellow 125 Hz to 8000 Hz. Women vocal cords are generally thinner and shorter than men's, which is the reason why the female frequency of vibration (or pitch) is normally higher (Egan, 1972). The male voice obviously contains lower-frequency energy than the female voice. This occurs because of a longer opening in male vocal cords which produce a lower driving frequency to the voice system. (Barron, 1993).

Table 2.2 Intelligibility rating and relations among STI values .

Intelligibility rating	Ranges of STI values
Excellent	> 0.75
Good	0.60-0.75
Fair	0.45-0.60
Poor	0.30-0.45
Bad	<0.30

Source: Steeneken, 2008

As a brief, Scavone(1999) claims that all these parameters are involved in the nature of acoustics to establish the most pleasant performances in halls and auditoriums. Designing to achieve ‘good acoustics’ always requires a deep understanding of acoustic parameters and their relations with geometry and material configurations, which are important issues to be concerned in the very beginning of the design process. Consequently, listing criteria for good acoustics were given below in order;

Optimum RT is a compromise between clarity (requiring short reverberation time), sound intensity (requiring a high reverberant level), and liveness (requiring a long reverberation time).The optimum RT of an auditorium is dependent on the use for which it is designed. In addition to the attributes good acoustics, spatial impression and EDT are important. The spatial impression is dependent on contributions to the early reflections from above and especially from the sides. The initial rate of decay of reverberation is apparently more perceptually important than the total reverberation time. The greater the EDT (up to two seconds) needs to the greater the preference for the halls. Above two seconds, the trend it reversed. Narrow halls are generally preferred to wide ones. (Scavone, 1999) Echoes, flutter echoes, sound focusing, sound shadows, and background noise should be avoided in design.

2.3 Criteria Affecting the Acoustical Features of Historical Baths

The acoustical properties that make a space good for speech are often the same as those that make it poor for music, and vice versa. The science of acoustics and the arts of architecture and music are hereby blended. From the stand point of acoustical analyses of historical baths consist of some general considerations which are material properties, microclimatic features volume and geometry of baths, and occupied-no occupied conditions.

The principal subject of this study is to present and discuss comparisons between past and present acoustical features of building in terms of various room acoustical indices. Before making the comparisons, it is worthwhile briefly to consider a few aspects of the process of modeling a Turkish bath and making calculations with this modeled room. Like virtually all computer models, ODEON works from a description of a room's geometry and absorption. The results of a calculation will obviously depend on how these are approximated.

2.3.1 Acoustical Properties of Materials

The rate at which sound is absorbed in a room is a prime factor in reducing noise and controlling reverberation. All materials used in construction of building absorb some sound, but proper acoustical control often requires the use of materials that have been especially designed to function primarily known as “acoustical absorbers”. Sound is absorbed by a mechanism which converts the sound into other forms of an energy and ultimately into heat. High porosity and low dense, many materials such as mineral wools, pads, carpets expanded polystyrenes and blankets have a multitude of small deeply penetrating intercommunicating pores.

The sound waves can readily propagate themselves into these interstices, where portion of the sound energy is converted into heat by fractional and viscous resistance within the pores and by vibration of the small fibers of the material and that means these materials present high sound absorptive characteristics.. On the contrary, low porosity and high dense materials such as marble tiles; cement based plasters, metal and glass…*etc.* present low sound absorptive characteristics.

The efficiency of a material in absorbing acoustical energy at specified frequency is given by its *sound absorption coefficient (α)* at that frequency. This quantity is the fractional part of the energy of incident sound wave absorbed (not reflected) by the material. Thus, if sound waves strike a material, and if 55 percent of the incident acoustical energy is absorbed and 45 percent is reflected, the absorption coefficient of the material is 0.55. The absorption coefficient can take values between 0 and 1, 1 is being a perfect absorber and 0 is being totally reflective (Figure 2.8) (Ecophon group, 2008).

1. Transmitted energy
2. Converted energy
3. Incident energy
4. Reflected energy

* Absorption coefficient: α

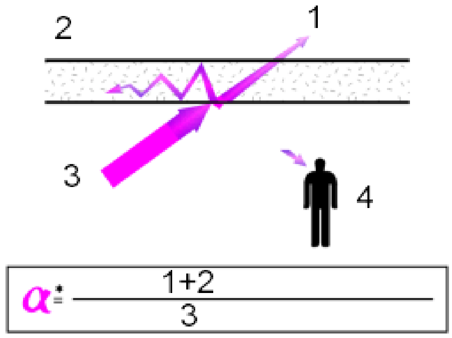


Figure 2.8 The illustration of the sound wave showing the direction and conversion

Source : Archives of the Ecophon group, 2008

The sound absorption coefficients for some materials were summarized in Table 2.3 The sound absorption properties of historical materials, such as historic brick, brick mortar and plasters are not known yet. The determination of sound absorption coefficient for lime based historical plaster is the subject of this thesis, which establishes the fundamental data for the acoustical analyses. In terms of acoustical properties, the selection of materials and the finishing of interior surface for the *AS- IS* case condition were defined by the absorption coefficients from 63 to 8000 Hz. Materials were selected from an extendable material library of Odeon.

Table 2.3 Representative absorption coefficients of surfaces.

Material	Absorption coefficient α					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Brick, unglazed	0.03	0.03	0.03	0.04	0.05	0.07
Plaster, gypsum or lime, on brick	0.01	0.02	0.02	0.03	0.04	0.05
On concrete block	0.12	0.09	0.07	0.05	0.05	0.04
Concrete block, coarse	0.36	0.44	0.31	0.29	0.39	0.25
Painted	0.10	0.05	0.06	0.07	0.09	0.08
Plywood, 1-cm-thick paneling	0.28	0.22	0.17	0.09	0.10	0.11
Cork, 2.5 cm thick with airspace behind	0.14	0.25	0.40	0.25	0.34	0.21
Glass, typical window	0.35	0.25	0.18	0.12	0.07	0.04
Drapery, lightweight, flat on wall	0.03	0.04	0.11	0.17	0.24	0.35
Heavyweight, draped to half area	0.14	0.35	0.55	0.72	0.70	0.65
Floor, concrete	0.01	0.01	0.02	0.02	0.02	0.02
Linoleum on	0.02	0.03	0.03	0.03	0.03	0.02
Heavy carpet on	0.02	0.06	0.14	0.37	0.66	0.65
Wood	0.15	0.11	0.10	0.07	0.06	0.07
Ceiling, gypsum board	0.29	0.10	0.05	0.04	0.07	0.09
Plastered	0.14	0.10	0.06	0.05	0.04	0.03
Plywood, 1 cm thick	0.28	0.22	0.17	0.09	0.10	0.11
Suspended acoustical tile, 2 cm thick	0.76	0.93	0.83	0.99	0.99	0.94
Gravel, loose and moist, 10 cm thick	0.25	0.60	0.65	0.70	0.75	0.80
Grass, 5 cm high	0.11	0.26	0.60	0.69	0.92	0.99
Rough soil	0.15	0.25	0.40	0.55	0.60	0.60
Water surface, as in a pool	0.01	0.01	0.01	0.02	0.02	0.03

Source: Egan, 1972

The Wikipedia Encyclopedia (2008) defines the noise reduction coefficient (commonly abbreviated NRC) is a scalar representation of the amount of sound energy absorbed upon striking a particular surface. An NRC of 0 indicates perfect reflection; an NRC of 1 indicates perfect absorption. In particular, it is the average of four sound absorption coefficients of the particular surface at frequencies of 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz. These frequencies encompass the fundamental frequencies and first few overtones of typical human speech, and, therefore, the NRC provides a decent and simple quantification of how well the particular surface will absorb the human voice. A more broad frequency range should be considered for applications such as music or controlling mechanical noise.

2.3.2 Geometry Evaluation

The most important architectural acoustics features are dome system and barrel vaults. Architectural forms of Turkish baths consist of some components which are dome, vault, barrel vault and arches. It is expected that these components of the building have a bad influence in terms of acoustical principles. And also these are unwanted features to have a high ceiling and most of the area is clad with marble which is less absorptive material. Egan (1988) claims that concave shapes cause the reflected sound to converge at a focal point. For example, sound energy may be concentrated in certain areas (called focusing) or reflected along smooth concave surfaces (called creep echo, or the "whispering gallery effect" because low voice levels can be heard at considerable distance away). Note that focusing can be more noticeable for low frequency, sound energy because most finishing materials are less absorptive at low frequency".

Long (2006) further explains that the acoustical properties that make a room good for speech are often the same as those that make it poor for music, and vice versa. For good speech intelligibility, room volumes and RT should be low. Conversely, rooms designed for listening to unamplified music require longer RT, higher volumes, lateral rather than overhead reflections, and high diffusion. Rooms designed for mixed uses require a judicious compromise between the needs of speech and music. Buildings of this type, including auditoria, theaters, and religious spaces are among the most architecturally diverse of all spaces and the most challenging to design.

Also Long (2006) states that when a place is designed for speech, strong overhead reflections are overhead, whereas for music, a ceiling that diffuses the sound aids in the sense of envelopment, or feeling surrounded by the sound, is best. A flat ceiling can yield excellent results for speech, if it is not too high and if the floor rake is sufficient. Where the ceilings are very high or when there are ceilings at different heights, as there is the case in some religious structures, the highest surfaces should be the first choice to receive the absorptive treatment. These spaces sound best, if the reverberation time matches. Application of absorption to the whole area may not be required, but if some is treated the rest should maintain a consistent appearance whether treated or not. Where a highly diffuse ceiling is used, clarity is likely to suffer in the rear of the auditorium and in the balcony seats during unamplified use.

Occupancy condition also affects the acoustical features of interiors. For instance, in the fully occupied halls, students dressed in formally and seated in tablet armchairs are presented 0.49 and 0.84 sound absorption coefficients "α" at 500 Hz and 1000 Hz respectively. On the contrary, the same hall and the same armchairs for the unoccupied conditions, in other words, without any students, are presented 0.22 and 0.39 sound absorption coefficients "α" at 500 Hz and 1000 Hz respectively (Egan, 1988). According to this example we can say that occupancy conditions increase the sound absorption surfaces in the space depending on the existence of people. During the study, all examinations were done for the *"unoccupied situation"* of the structures, because "α"of a naked and wet person and type of swimming dress, has not been well known yet. Further studies are required on these subjects.

2.3.3 Microclimate Features

The Turkish baths have different climate conditions such as wet space, high degree temperature and high level relative humidity. And all these conditions make these spaces inappropriate in regards acoustical properties. During the research, all calculation parameters were set automatically but some parameters were changed because of special cases, which are temperature (40 C°) and relative humidity of Turkish baths (100%). Dispersion of acoustic waves has not been considered.

2.4 3D Computer Modeling and Acoustical Simulation Analyses

3-D computer modeling of room acoustics become an important investigation tool for acousticians and researchers over the last few decades. Several software programs exist and have been repeatedly tested and compared. These are *AutoCAD* and *ODEON*. *AutoCAD* is one of the most commonly used programs for drawings. On the other hand *ODEON* is used for acoustical analyses. AutoCAD is the program that is easily adapted to the *ODEON* software. And also, *ODEON* was developed by the department of acoustic technology and six Danish consulting companies back in 1984 with the purpose of providing reliable and easy to use room acoustics prediction software. That's why; this research was carried on by the *AutoCAD* and *ODEON* software.

A special care should be given to the 3D acoustical simulation studies, especially for the historical structures, using sophisticated software. The correct definition of spaces in terms of materials, geometrical formation, microclimatic conditions and the state occupied conditions is essential for the correct analyses of the acoustical environment. Because, the virtual state of acoustical environment should represent the real state of the same acoustical environment in order to enhance the accuracy of the acoustical analyses; in other words, the results obtained from 3D acoustical simulation, should correspond to the ones obtained by in-situ recordings. The studies on 3D acoustical simulation of historical structures, such as Sokullu and Süleymaniye mosques and Saint Irene Byzantine church (Istanbul), have shown that the simulated acoustical data, examined by *ODEON* software, were consistent with the in-situ acoustical recordings and auralizations (Weitze, Christensen, Rindel, Gade, 2001) On the other hand, there is lack of information on the acoustical properties of historic materials, such as historic brick, brick mortar, plasters, *etc*...

The knowledge on the sound absorption characteristics of historic materials is extremely-important for the assessment of the real state of their acoustical environment. The studies on determination of acousto-physical properties of historic materials are, therefore, needed in order to achieve the sound absorption coefficient data for historic materials to be used as input at this software.

2.4.1 Calculation Methods of Acoustical Analyses

Rindel (2002) states that development of the design tools is described in three sections considering physical models, scale models, and computer models. Computer models were evaluated by using the different methods which were started with the ray tracing method and the image source method, later, radiosity models were developed and finally, the hybrid methods were used. These methods were described in this chapter.

The Ray Tracing Method uses a large number of particles, which are emitted in various directions from a source point. The particles are traced around the room loosing energy at each reflection according to the absorption coefficient of the surface. When a particle hits a surface it is reflected, which means that a new direction of propagation is determined. This is called a specular reflection. In order to obtain a calculation result related to a specific receiver position it is necessary either to define an area or a volume around the receiver in order to catch the particles when travelling by, or the sound rays may be considered the axis of a wedge or pyramid. In any case there is a risk of collecting false reflections and risk of the fact that some possible reflection paths may not be found. However, it was not possible to obtain a reasonable accuracy with this technique.

The Image Source Method is based on the principle that a specular reflection can be constructed geometrically by mirroring the source in the plane of the reflecting surface. In a rectangular box-shaped room it is very simple to construct all image sources up to a certain order of reflection (Allen, Berkley, 1979; Borish, 1984). But in an arbitrary room the number of possible image sources increases exponentially with the order of reflection, and thus the method is not suitable for rooms like concert halls where reflection orders of several hundred are relevant for the audible reverberant decay. Rindel (2000) cited that the advantage of the image source method is that it is very accurate, but if the room is not a simple rectangular box there is a problem. For this reason image source models are only used for simple rectangular rooms or in such cases where low order reflections are sufficient, e.g. for design of loudspeaker systems in non-reverberant enclosures (Allen, Berkley, 1979; Borish, 1984)

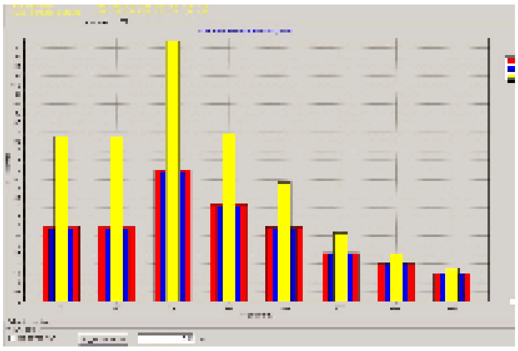
The principle of *the Radiosity Model* is that the reflected sound from a surface is represented by a large number of source points covering the surface and radiating according to some directivity pattern, typically a random distribution of directions. This method has also been used as an efficient way to model the scattered part of the early reflected sound (Christensen, 2000; Rindel 2002).

The disadvantages of the classical methods have led to development of *the Hybrid models,* which combine the best features of two or more methods. Thus modern computer models can create reliable results with only modest calculation times. The inclusion of scattering effects and angle dependent reflection with phase shifts has made it possible to calculate impulse responses with a high degree of realism (Christensen, 2000; Rindel 2002).

The ODEON model used in this work belongs to the 'hybrid' type of models, which contains elements of both ray tracing and image source models. It is based on the idea that an efficient way to find branches of the image source tree having high probabilities of containing visible image sources is to trace rays from the source and note the surfaces they hit. The reflection sequences thus generated are then tested as to whether they give a contribution at the chosen receiver position, in line with image source theory. The finite number of rays used places an upper limit on the length of accurate reflectogram obtainable. Thereafter, some other method has to be used to generate a reverberant tail. In a complete calculation the last early reflection (from an image source) will typically arrive after the first late reflection (from a secondary source), so there will be a time interval where the two methods overlap (ODEON combined 8.5, 2008).

ODEON uses two methods for displaying the results. The first one is the Quick Estimate method which estimates a mean absorption coefficient, to give an estimate of the reverberation time (Figure 2.9a). Instead of simply taking the areas of the surfaces and multiplying by the corresponding absorption coefficients to obtain the total absorption in the room, software also sends out 'particles' from the source, reflecting them in the room keeping a count on how many times they hit each surface(ODEON combined 8.5, 2008).

The second one is the global Estimate method which estimates the global reverberation times, the room volume and the mean free path and generates estimation of decay curves (Figure 2.9b). Particles are sent out in random directions from the source and reflected using the ‘Late ray’ reflection method. To ensure that calculation results were reliable, it was essential that geometries should be consistent. Program includes a number of tools for geometry verification; the verification of the surfaces whether they were completely watertight or not, was checked by the ray tracing method. (Figure 2.10a) (ODEON combined 8.5, 2008).



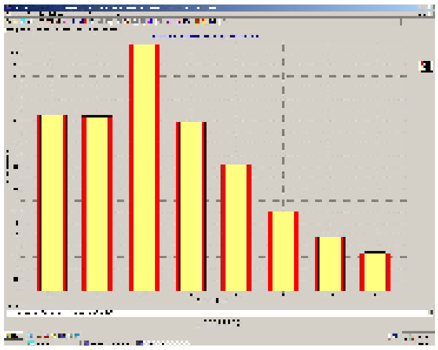


Figure 2.9.a) The graphs showing the Quick estimate calculation result (at the left) and b) Global estimate calculation result (at right)

Source: http://www.odeon.dk

The perception of sound by a person sitting at any place in the caldarium space was simulated by using the "Grid response" calculation method and the results were mapped in terms of all acoustical parameters. With a computer model it is straightforward to calculate the response at a large number of receivers distributed in a grid that covers the audience area. An example is shown in Figure. 2.10b It can be extremely useful to see a mapping of the spatial distribution of acoustical parameters. Uneven sound distribution and acoustically weak spots can easily be localized and appropriate countermeasures can be taken.

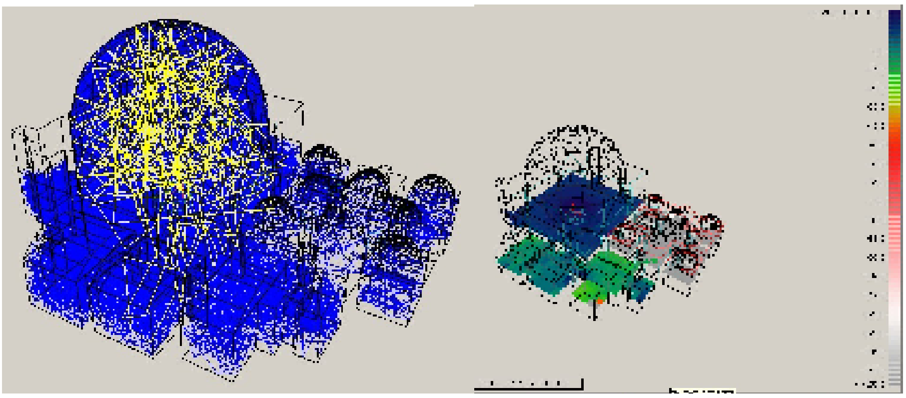


Figure 2.10 a) The Ray tracing method applied for the acoustical analyses of the Kadı Hamamı and b) distribution graph of C80 at 1000 Hz in Kadı Hamamı.

CHAPTER 3

MATERIAL AND METHOD

Here are presented the material and method of the study. The former describes the architectural features of two historical Turkish baths, Şengül Hamamı and Kadı Hamamı, examined as the case studies and their interior finishing materials. The latter then presents the laboratory tests to determine the sound absorption coefficient of the historical plasters at different moisture contents. The methods of 3-D modeling and acoustical simulation used for the acoustical assessment of these bath structures are also explained here.

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3.1 Case Studies: Şengül Hamamı and Kadı Hamamı

In this research, two historical Turkish baths belonging to the Ottoman period were examined. The first one is the Şengül Hamamı which is a typical double public bath in the province of Ankara and the second one is the Kadı Hamamı which is a typical single public bath, located in province of Diyarbakır. Both of them are 15^{th} century Turkish baths, still representing the continuous experience of Turkish bathing culture in Anatolia. They were, therefore, selected for this study in order to examine the historical acoustical features of Turkish baths by means of 3-D computer modeling and acoustics simulation method.

The Şengül Hamamı consists of two separate sections for men and women (Figure 2.1). The caldarium and tepidarium spaces of women's section have the total volume of $714m^3$ with $900m^2$ effective surface area. The total volume of caldarium and tepidarium spaces for the men's section is $508m^3$ with $840m^2$ effective surface area. Men's section has a pool ornamented with a fountain at undressing room.

The structure was constructed with stone masonry walls with brick transitions and brick upper structure (Figures 3.1-3.3). The superstructure of Şengül Hamamı consisted of brick domes, vaults and arches. The interior of the structure has been recently repaired. The floors of the structure and the lower parts of walls were covered with marble slabs while the remaining wall and dome surfaces were covered with oil painted cement-based plaster.

Kadı Hamamı is a typical single public Turkish bath. It was also called as "Eşbek Hamamı". The structure was constructed with stone masonry walls with brick transitions and brick upper structure. The caldarium and tepidarium spaces have the total volume of $2000m^3$ with $1282m^2$ effective surface area (Figures 3.4 -3.5).

The acoustical analyses of these two structures were based on three cases: The first one was the analysis of "AS-IS case" representing the present acoustical conditions of the interiors after the structure was repaired with contemporary cement-based materials. The second one was "ORIGINAL case" representing the original acoustical features of interiors and based on an assumption that the interiors were repaired with materials compatible with historical ones; in other words, all interior surfaces were assumed to be kept as original. The third one was the "REPAIR case" representing the acoustical conditions of interiors when the interiors were assumed to be repaired with compatible plasters while the lower parts of walls were clad by marble slabs up to 1.50m - 2.00m height. The cladding of walls with marble was the common trend of recent repairs in order to improve the water impermeability at the lower parts of walls. The analysis of the REPAIR case was, therefore, needed in order to better understand the effect of marble-clad surfaces to the acoustical features of historical baths.

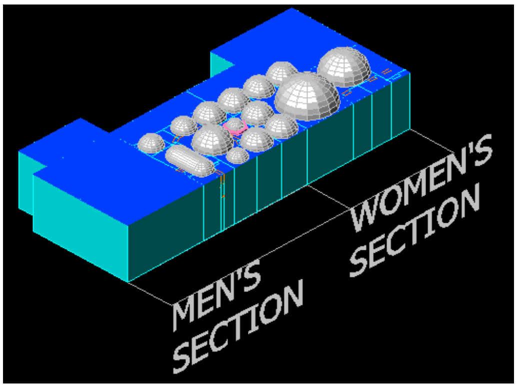

Figure 3.1 The 3-D model of Şengül Hamamı produced by AutoCAD for the acoustical analyses: axonometric views.

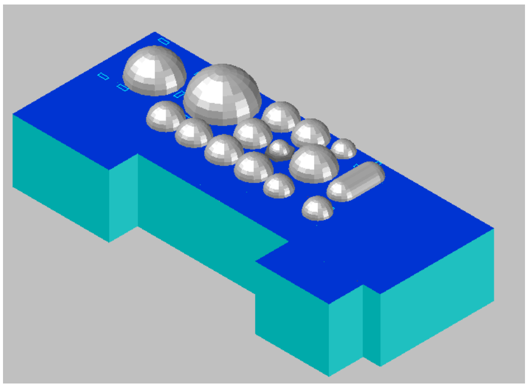

Figure 3.2 The 3-D model of Şengül Hamamı produced by AutoCAD for the acoustical analyses: axonometric views.

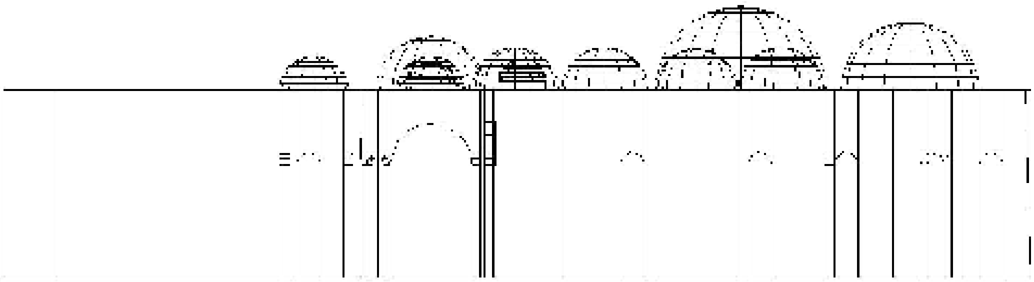

Figure 3.3 The wire frame model the Şengül Hamamı drawn by AutoCAD for acoustical simulation analyses: section view

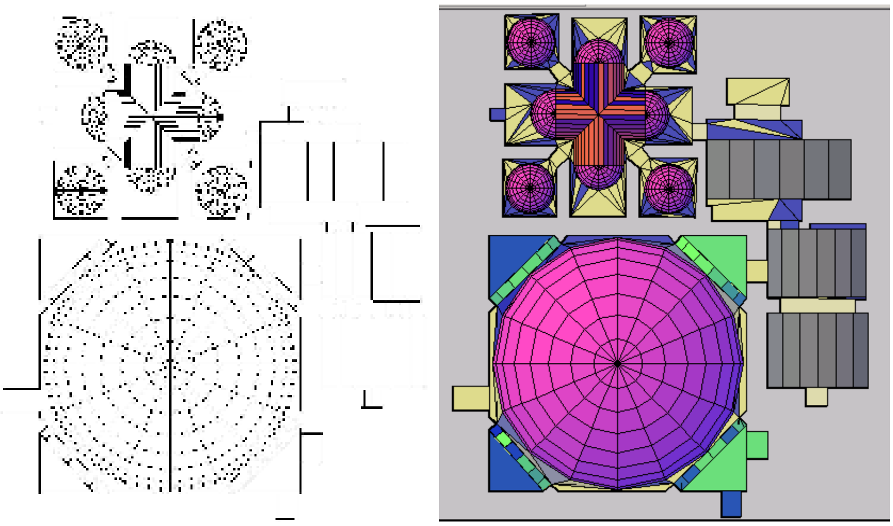

Figure 3.4 The wire frame model of the Kadı Hamamı drawn by AutoCAD for acoustical simulation analyses: the top view.

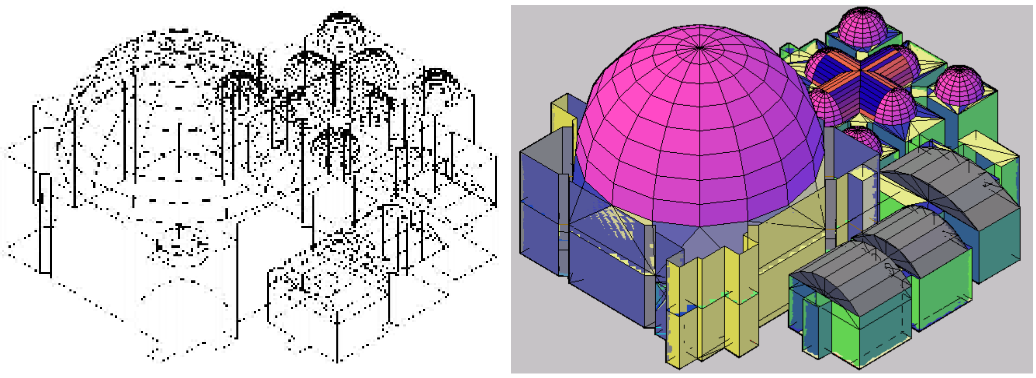

Figure 3.5 The wireframe model of the Kadı Hamamı drawn by AutoCAD: the axonometric view.

3.2 Determination of Sound Absorption Coefficient of Materials

The relationship between the sound absorption coefficient of historical plasters and their moisture content was investigated by means of laboratory tests. These tests were conducted on historical lime plaster samples collected from the caldarium space of Amasya Hızır Paşa Hamamı, belonging to the same period of the bath structures under study. The samples consisted of 3 plaster layers with 3.5 cm-thick in total (Figure 3.6) and each having similar physical properties, such as the mean value of 1.27 g/cm^3 as bulk density and of 52% as effective porosity (MCL, 2005). Since the interior of the structure was very humid, the materials should be in equilibrium in such wet conditions. Therefore, the sound absorption coefficient values (α) were examined both for dry (α_d), damp (α_{85}) and wet (α_{100}) conditions.

Figure 3.6 Views from the historical lime plaster samples collected from Amasya Hızır Paşa Hamamı

The process was started with measuring of dry weight of the sample. For this purpose the sample was put in desiccator that has $CaCl_2$, waited until constant weight was obtained, this weight is dry weight (Figures 3.7 a, b). When the sample was achieved to a constant mass at 85% RH, which was provided by $ZnSO_4$ solution in a desiccators, it assumed to be damp with an equilibrium moisture content of 4% by weight. This is a reliable situation for the calculations of α value for a completely damp porous material. When the sample was left at 100%RH, it assumed to be almost wet with an equilibrium moisture content of 7.4% by weight. However, this is not a reliable situation since the pores in the material were partially filled with water. The α_{85} value of historical plasters, therefore, represents the real sound absorption characteristics of historical plaster.

The sound absorption coefficients were determined by Standing Wave Method using an impedance tube. Measurements were carried on circular-cut dry, damp and wet samples of 70 mm diameter in the frequency range from 100 Hz to 2 kHz (the 1/3 octave bandwidth) (Figure 3.8). Standing wave (impedance tube) method was designed for measuring sound absorption coefficient and specific acoustic impedance of small circular samples, normally in the frequency of 1/3 Octave bandwidth (BSI BS EN ISO 10534-2, 2001). The acoustic impedance of a material describes its reflective and absorptive properties. During the test, the one-microphone transfer-function (impedance tube) method was used. The experimental set-up of the impedance tube measurements was given in Figure 3.8.

Figure 3.7 a) Samples kept in desiccators in 30%RH, 85%RH and 100%RH conditions (at left).

b) Samples were weighed till reaching a constant mass in dry, damp and wet states (at right)

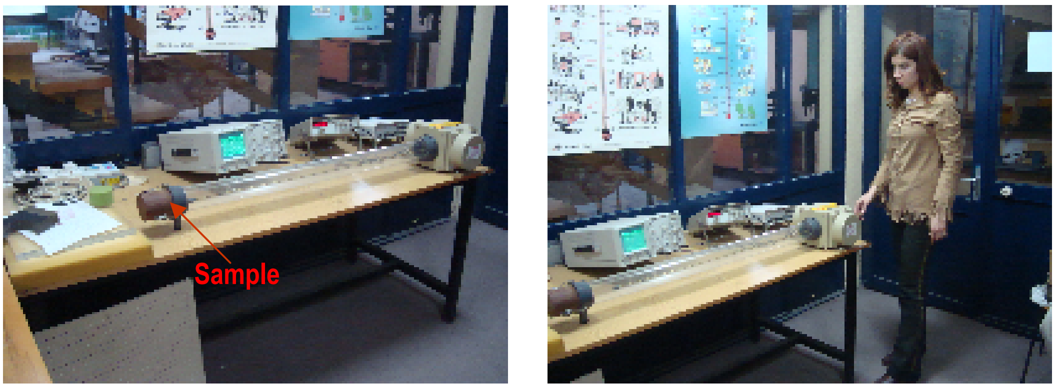

Figure 3.8 The experimental set up for the determination of the sound absorption coefficients by standing wave method showing the sample was placed in the holder of impedance tube.

3.3 3-D Modeling and Acoustical Simulation

The 3-D modelling and acoustical simulation method was carried out to define the acoustical characteristics of the caldarium and tepidarium sections of Şengül Hamamı and Kadı Hamamı. Their audial performances were evaluated by taking into consideration of volume, use of materials, environmental conditions and positions of sound source and receiver.

Mainly three cases, AS-IS, ORIGINAL and REPAIR cases were analyzed in terms of their virtual acoustical environment. Both for the AS-IS and ORIGINAL cases, the floors were marble-clad and dome lights were made of glass. For the AS-IS case, the lower parts of wall till 1.50m height was marble-clad while the wall and dome surfaces remained were covered with cement-based plasters with oil paint. For the ORIGINAL case, all wall and dome surfaces were thought to be repaired with lime-based plasters compatible with historical ones. The REPAIR case was also examined in order to better understand the acoustical effect of a common repair trend, which is the covering the lower parts of walls with marble slabs.

The sound absorption coefficient data for marble, glass and oil painted cement-based plaster, required for the acoustical modeling, were taken from the literature (Egan, 1988, Long, 2006), while the experimental data obtained in this study for the damp historical lime plaster was used as input to software for ORIGINAL case. These three cases were examined for constant microclimatic conditions of 40^{o}C and 100%RH.

During the modelling, a special care was also given to the geometric forms of spaces, such as domes, vaults, arches. The 3D computer modelling of structures by means of their detailed computer drawings representing the real geometric layout of spaces was produced by *AutoCAD 2007*. These models were, then, transferred to ODEON combined 8.5 software for the analyses of 3-D acoustical simulation. The acoustical simulation was based on the acceptation that the sound source was located at the centre of caldarium, on the elevated marble platform (*göbektaşı*), while the single point receiver was 6 m away from the source, located in iwan. The locations of the sound source and the receiver were shown in Figures 3.9 and 3.10 for the Şengül Hamamı and in Figure 3.11 for the Kadı Hamamı. The ear level of a human head was accepted to be +1.1m height while he or she was sitting. The single point receiver was, therefore, placed at 1.1m height and the sound source with a gain of 90 dB was placed at the height of 1.5m since the level elevated platform was +0.40m high above the floor level. The speech and musical performances of Şengül Hamamı and Kadı Hamamı were examined at the receiver location in terms of basic acoustical parameters; reverberation time (RT), early decay time (EDT), lateral fraction (LF80), clarity (C80), speech transmission index (STI) (Egan, 1988; ISO 3382, 1997; Long, 2006). The analyses were done under the unoccupied situation of the structures.

Figure 3.9 Front view of the sound source from the receiver in the model.

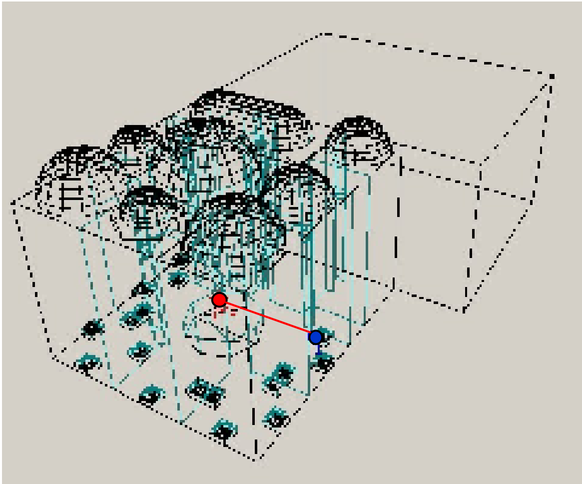

Figure 3.10 Odeon wire-frame model of the Sengül Hamamı men's section indicating the location of sound source (red dot) on the elevated platform of caldarium and the location of receiver (blue dot) at iwan in caldarium, 6m far away from the source.

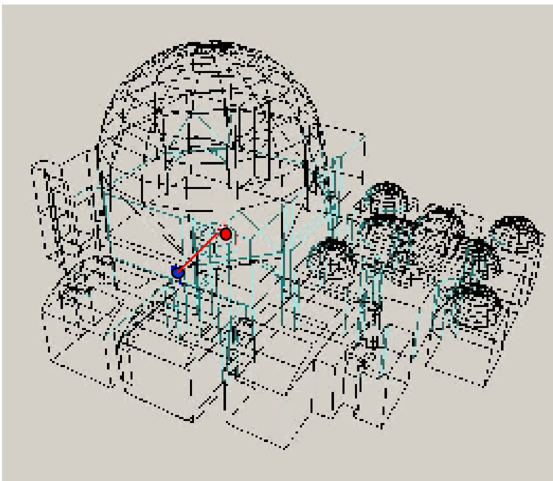

Figure 3.11 Odeon wire-frame model of the Kadı Hamamı indicating the location of sound source (red dot) on the elevated platform of caldarium and the location of receiver (blue dot) at iwan, 6m away from the source.

The verification of the surfaces whether they were completely watertight or not, was checked by the ray tracing method. The mean of the reverberation time for the caldarium and tepidarium spaces was calculated as the "Global estimate reverberation time". The perception of sound by a person sitting at any place in the caldarium space was simulated by using the by the “Grid response” calculation method and the results were mapped in terms of basic acoustical parameters; reverberation time (RT), early decay time (EDT), lateral fraction (LF80), clarity (C80), speech transmission index (STI). The data was processed for the octave band center frequencies of 63, 125, 250, 500, 1000, 2000, 4000 and 8000 Hz (1/1 octave bands). The emphasis was given to the mid frequency region, i.e., 500 Hz and 1000 Hz, which are considered to characterize acoustical properties of spaces.

CHAPTER 4

RESULTS

In this chapter, the results were presented together or in sequence with figures and tables, and then summarized in the following sections. The experimental data obtained on the sound absorption characteristics of historical plasters were given together with the sound absorption characteristics of contemporary plasters, allowing an opportunity for their comparisons. The results of acoustical simulation analyses were brought together in terms of basic acoustical parameters in order to define the acoustical features of Şengül Hamamı and Kadı Hamamı for ORIGINAL, AS-IS and REPAIR cases. The sum up of this knowledge was used to demonstrate the differences between the ORIGINAL and AS-IS cases of historical baths precisely.

4.1 Sound Absorption Coefficient Values of Historical Lime Plasters Used in Historical Turkish Baths

The results of the laboratory analyses were summarized in Figure 4.1, Table 4.1 and Table 4.2. The experimental data obtained according to the frequencies of 1/3 octave bands were given in Table 1, both for the dry, damp and wet historical lime plasters. For the center frequency of 1/3 octave bands, the sound absorption coefficient values for the dry and damp historical lime plaster samples were measured to be in the ranges of 0.08 and 0.33 and in the ranges of 0.11 and 0.37, respectively. On the other hand, the sound absorption coefficients of wet samples (α_{100}) were found to be lower than the dry and damp samples within the ranges of 0.06 and 0.18.

Table 4.1 Sound absorption coefficients for dry (α_d), damp (α_{85}) and wet (α_{100}) historical lime plaster versus frequency of 1/3 octave bands.

Historical Lime Plaster	Frequency, Hz													
	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000
α_d	0.08	0.10	0.10	0.19	0.12	0.19	0.24	0.25	0.20	0.26	0.29	0.31	0.30	0.33
α_{85}	0.11	0.13	0.11	0.26	0.14	0.15	0.12	0.17	0.15	0.22	0.29	0.29	0.37	0.30
α_{100}	0.09	0.06	0.06	0.10	0.08	0.09	0.12	0.09	0.18	0.08	0.17	0.08	0.14	0.15

The sound absorption coefficients of historic lime plasters at 125Hz, 250Hz, 500Hz, 1000Hz and 2000Hz octave bands center frequencies and their noise reduction coefficient (NRC), which is the mean of sound absorption coefficients at 125Hz, 250Hz, 500Hz, 1000Hz and 2000Hz, were presented in Table 4.2 and Figure 4.1. The sound absorption coefficients of dry sample (α_d) at 500Hz, 1000Hz and 2000Hz were found to be 0.23, 0.29 and 0.32, respectively, with noise reduction coefficient (NRC) of 0.25. The sound absorption coefficients of damp sample (α_{85}) at 500Hz, 1000Hz and 2000Hz were found to be 0.15, 0.27 and 0.34, respectively, with noise reduction coefficient (NRC) of 0.23. The sound absorption coefficients of wet sample (α_{100}) at 500Hz, 1000Hz and 2000Hz were found to be 0.13, 0.11 and 0.14, respectively, with noise reduction coefficient (NRC) of 0.12. The average sound absorption coefficient values of dry, damp and wet samples were calculated to be 0.26, 0.21 and 0.12 at mid-frequency (between 500Hz and 100Hz). An increase in more moisture content of historical plasters, seemed to decrease their sound absorption properties (Figure 4.1).

Table 4.2 Sound absorption coefficients of dry (α_d), damp (α_{85}) and wet (α_{100}) historical lime plasters at 125Hz, 250Hz, 500Hz, 1000Hz and 2000Hz octave bands center frequencies, and the noise reduction coefficient (NRC) of historic lime plasters, representing the mean of their sound absorption coefficients at 125Hz, 250Hz, 500Hz, 1000Hz and 2000Hz.

Historical Lime Plasters	Sound absorption coefficient (α)					Noise reduction coefficient (NRC)
	125 Hz	250 Hz	500Hz	1000Hz	2000Hz	The mean of 250Hz-2000Hz
Dry sample (at 30% RH)	0.10	0.17	0.23	0.29	0.32	0.25
Damp sample (at 85% RH)	0.12	0.18	0.15	0.27	0.34	0.23
Wet sample (at 100% RH)	0.07	0.09	0.13	0.11	0.14	0.12

The sound absorption coefficient values of historic lime plasters obtained by the laboratory tests were presented in Figure 4.1 at 1/1 octave band center frequency together with the sound absorption coefficients of some contemporary materials used in repair works, such as cement-based plaster, marble and 3mm-thick glass, taken from the literature (Cowan, 2000; Egan, 1988; Long, 2006). According to the sound absorption coefficient list of various materials prepared by Egan (1988), the sound absorption coefficient of marble at 500Hz, 1000Hz and 2000Hz were 0.01, 0.01 and 0.02; for 3mm-thick glass, they were 0.03, 0.03 and 0.02; for the oil painted cement-based plaster, they were 0.02, 0.03 and 0.03, respectively. The historical lime-based plasters seemed to be considerably sound absorptive than the contemporary materials.

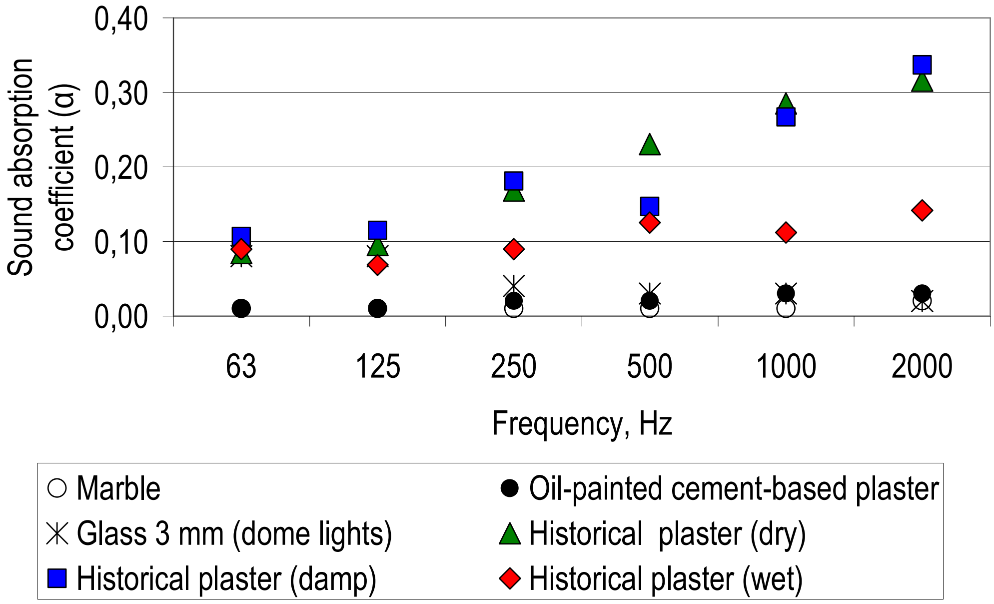

Figure 4.1 Absorption coefficients of marble, glass, oil-painted cement-based plaster and historical lime plaster versus frequency, Hz. The data for marble, glass, oil painted cement-based plaster were taken from the literature (Egan, 1988).

4.2 Acoustical Features of Şengül Hamamı

In this part, under this heading, ORIGINAL, AS-IS and REPAIR cases were defined for Şengül Hamamı women's and men's sections in terms of basic acoustical parameters.

4.2.1 Original Case of Şengül Hamamı

The global reverberation time (GRT) values of the Şengül Hamamı women's section for the ORIGINAL case under unoccupied conditions were found to vary in the range of 0.6 s and 2.1 s in the frequencies of 1/1 octave bands (Figure 4.2). The GRT at 500Hz and 1000Hz were found to be 0.9 s and 2.1 s, respectively, with an average GRT of 1.5 s. at mid-frequency (Figure 4.2). On the other hand for the Şengül Hamamı men's section was found to vary in the range of 0.6 s -1.9 s (Figure 4.3)., and the GRT at 500Hz and 1000Hz were found to be 0.8 s and 1.9 s, respectively, with an average GRT of 1.3 s. at mid-frequency(Figure 4.3).

The point RT , EDT, LF80, C80 and STI values at mid-frequencies obtained for the specified receiver location in Şengül Hamamı women's and men's sections for the ORIGINAL case were summarized in Table 4.3. According to these results, at the women's section of Şengül Hamamı, the point RT values at 500 Hz and 1000 Hz were found to be 0.9 s and 2.4 s, respectively, with an average RT value of 1.7 s at mid-frequency. At the men's section, the point RT values at 500 Hz and 1000 Hz were found to be 0.8 s and 1.9 s, respectively, with an average RT value of 1.3 s at mid-frequency (Table 4.3).

EDT for Şengül Hamamı women's section was found to be 1s and 2.1 s, in 500 Hz and 1000 Hz, respectively, and 1.6 s for average of those values taken at 500 and 1000 Hz. EDT of men's section was found to be 0.9 s and 1.7 s, at 500 Hz and 1000 Hz, respectively, and 1.3 s for average of those values taken at 500 and 1000 Hz. When EDT values of Şengül Hamamı were compared with the RT values of the structure, it can be seen that EDT values were found to be consistent with RT values.

LF80 of the Şengül Hamamı women's section was found to be 0.214 and 0.253, at 500 Hz and 1000 Hz respectively, and 0.233 for an average of those values taken at 500 and 1000 Hz. And Lateral Fraction of the men's section of the building was found to be 0.207 s and 0.252, at 500 Hz and 1000 Hz, and the average values for mid-frequencies (500 Hz and 1000 Hz) were found to be 0.230 respectively.

f (Hz)	63	125	250	500	1000	2000	4000	8000
GRT	1.6	1.4	1.2	0.9	2.1	0.7	0.8	0.6

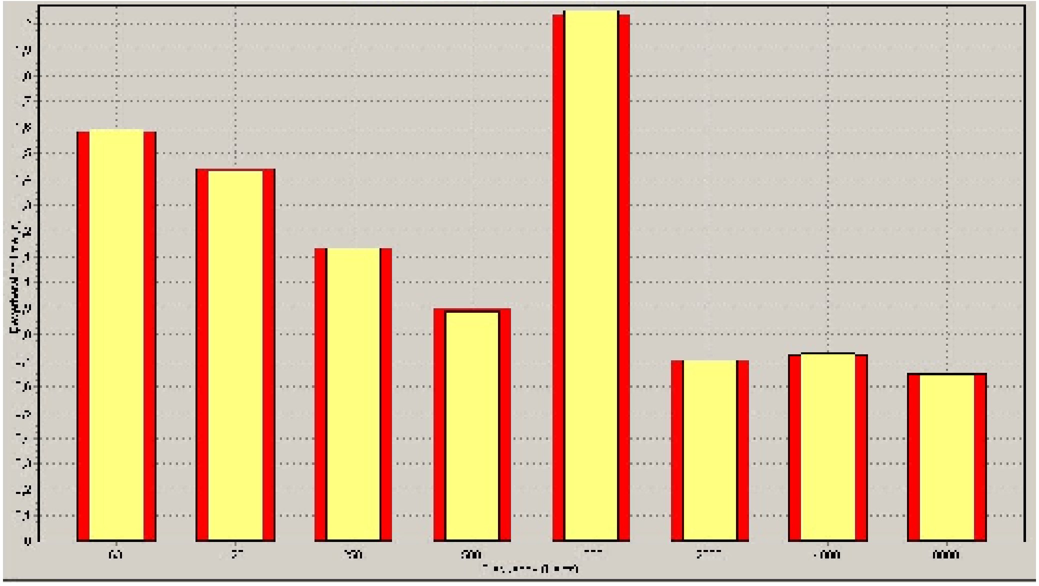

Figure 4.2 Bar chart showing global reverberation times in women's section of Şengül Hamamı between 63 Hz-8000 Hz for the ORIGINAL case (red color represents "T_{20}", yellow color represents "T_{30}")

f (Hz)	63	125	250	500	1000	2000	4000	8000
GRT	1.4	1.3	1.0	0.8	1.9	0.6	0.6	0.6

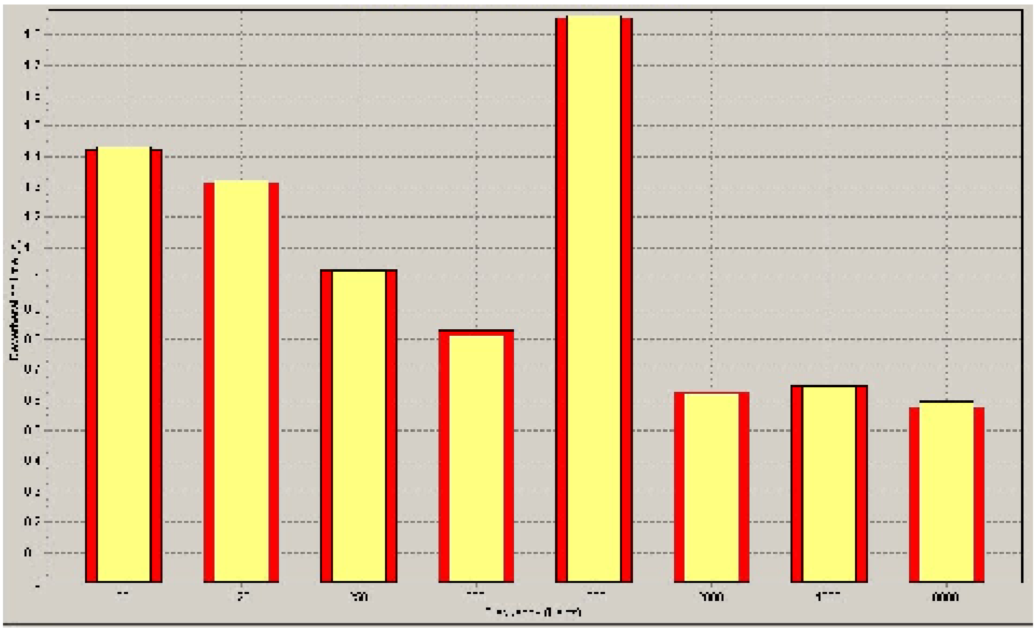

Figure 4.3 Bar chart showing global reverberation times in men's section of Şengül Hamamı between 63 Hz-8000 Hz for ORIGINAL case, (red color represents "T_{20}", yellow color represents "T_{30}")

Clarity (C80) values of the Şengül Hamamı women's section, in the building, were found to be 2.5 dB and -2.6 dB, at 500 Hz and 1000 Hz respectively, and -0.1 dB for average of those values of mid-frequencies at the specified receiver location. C80 values of the Şengül Hamamı in men's section was found to be 5.5 dB and -0.4 dB, at 500 Hz and 1000 Hz, respectively, and the average values for mid-frequencies (500 Hz and 1000 Hz) were found to be 2.6 dB, respectively.

According to Table 4.3, STI values of the Şengül Hamamı women's and men's section were found to be 0.54, 0.63 respectively at the specified receiver location.

Table 4.3 Results of RT, EDT, C80, LF80, STI values at 500 Hz and 1000Hz for the women's & men's sections of Şengül Hamamı calculated for the ORIGINAL case under unoccupied conditions, and their average values at the specified receiver location.

Acoustical Parameters	Women's Section ORIGINAL Case			Men's Section ORIGINAL Case		
	Frequency			Frequency		
	500	1000	Average	500	1000	Average
RT, s	0.9	2.4	1.7	0.8	1.9	1.3
EDT, s	1	2.1	1.6	0.9	1.7	1.3
LF80	0.214	0.253	0.233	0.207	0.252	0.230
C80, dB	2.5	-2.6	-0.1	5.5	-0.4	2.6
STI	0.54			0.63		
Volume, m^3	714			508		

4.2.2 AS-IS Case of Şengül Hamamı

The results of AS-IS case were summarized in Table 4.3. This case based on the all walls covering with contemporary cement based plaster, in the Şengül Hamamı women's and men's sections corresponding to the specified receiver location.

The global reverberation time (GRT) values of the Şengül Hamamı women's section for the ORIGINAL case were found to vary in the range of 1.6 s and 9.3 s in the frequencies of 1/1 octave bands (Figure 4.4). The GRT at 500Hz and 1000Hz were found to be 7.8 s and 5.8 s, respectively, with an average GRT of 6.8 s. at mid-frequency (Figure 4.4). On the other hand for the Şengül Hamamı men's section was found to vary in the range of 1.5 s and 7.9 s (Figure 4.5)., and the GRT at 500Hz and 1000Hz were found to be 6.4 s and 5.0 s, respectively, with an average GRT of 5.7 s. at mid-frequency(Figure 4.5).

According to these results, the point RT values at 500 Hz and 1000 Hz were found to be 7.8 s and 5.7 s, with an average RT value of 6.8 s at mid-frequency in Şengül Hamamı women's section, respectively. The point RT values at 500 Hz and 1000 Hz were found to be 6.5 s and 4.6 s, with an average RT value of 5.6 s at mid-frequency in Şengül Hamamı men's section, respectively (Table 4.4). According to results (Figures 4.4-4.5), it could be seen that much higher RT values in AS-IS case decrease considerably in the frequency range of 500 Hz-8000 Hz. This change in reverberation times can be attributed to air absorption in the high frequency range (Barron, 1998).

The results of the EDT at the specified receiver location were given in the Table 4.3. According to the table, the EDT values were not consistent with the global RT values for the whole space; EDT, individually, were found to be 7.5 s and 5.3 s, at 500 Hz and 1000 Hz, in women's section. These values were 5.8 s and 4.6 s, at 500 Hz and 1000 Hz, in men's section, respectively. The average values of women's and men's sections were found to be 6.4 s and 5.2 s, respectively for mid-frequencies (500 Hz and 1000 Hz) (Table 4.4).

According to Table 4.4, LF80 in the women's section, at the specified receiver location, at both 500 Hz and 1000 Hz were found to be same values as 0.269, so the average values were again 0.269. LF 80 values of men's section were found to be a little different from women's section; i.e. 0.261 for 500 Hz. 0.267 for 1000 Hz, and average value for mid-frequency was 0.264 (Table 4.3).

C80 values in women's section were found to be -8.2 dB at 500 Hz and -7 dB at 1000 Hz respectively, -7.6 dB as average of mid-frequencies. For the men's section C80 values were found to be -6.2dB at 500 Hz and -5.2 dB at 1000 Hz, the average value for mid-frequencies was found to be -5.2 dB (Table 4.4).

Speech transmission index (STI) values for women's and men's sections were 0.30 and 0.35, respectively, at the specified receiver locations (Table 4.4) which indicate poor speech intelligibility conditions at the specified receiver location.

Table 4.4 Results of RT, EDT, C80, LF80, STI values at 500 Hz and 1000Hz at the specified receiver location the women's & men's sections of Şengül Hamamı calculated for the AS-IS case under unoccupied conditions, and the average of those values taken at 500 and 1000 Hz

Acoustical Parameters	Şengül Hamamı Women's Section AS IS Case			Şengül Hamamı Men's Section AS IS Case		
	Frequency			Frequency		
	500	1000	Average	500	1000	Average
RT, s	7.8	5.7	6.8	6.5	4.6	5.6
EDT, s	7.5	5.3	6.4	5.8	4.6	5.2
LF80	0.269	0.269	0.269	0.261	0.267	0.264
C80, dB	-8.2	-7	-7.6	-6.2	-5.2	-5.7
STI		0.30			0.35	
Volume, m^3		714			508	

f (Hz)	63	125	250	500	1000	2000	4000	8000
GRT(s)	9.3	9.2	9.0	7.8	5.8	3.0	2.2	1.6

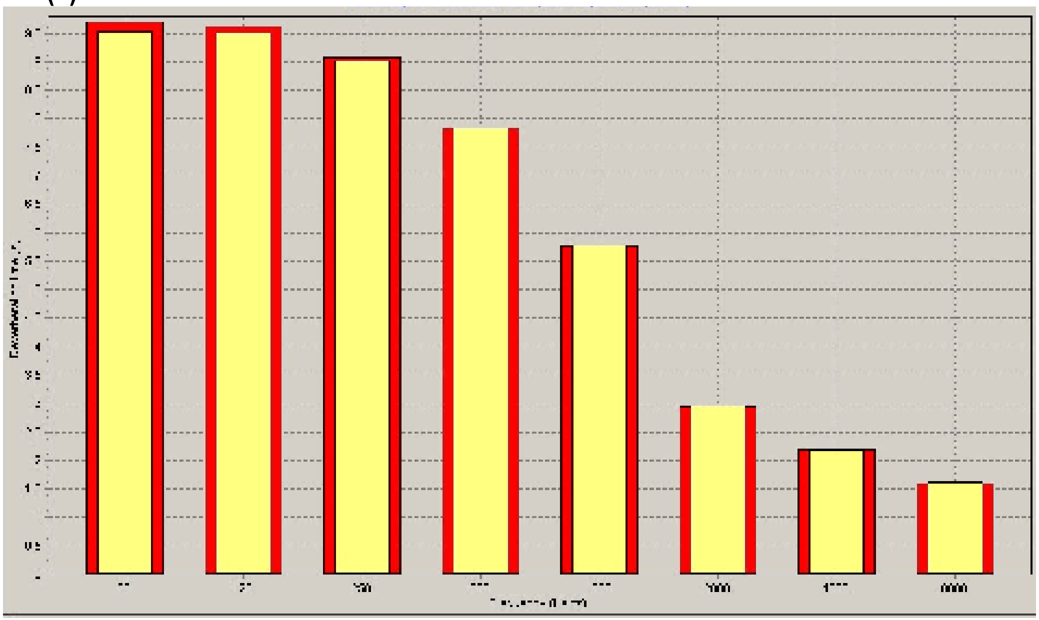

Figure 4.4 Bar chart showing global reverberation times in women's section of Şengül Hamamı between 63 Hz-8000 Hz for AS-IS case, (red color represents "T_{20}", yellow color represents "T_{30}")

f (Hz)	63	125	250	500	1000	2000	4000	8000
GRT(s)	7.9	7.8	7.4	6.4	5.0	2.5	2.0	1.5

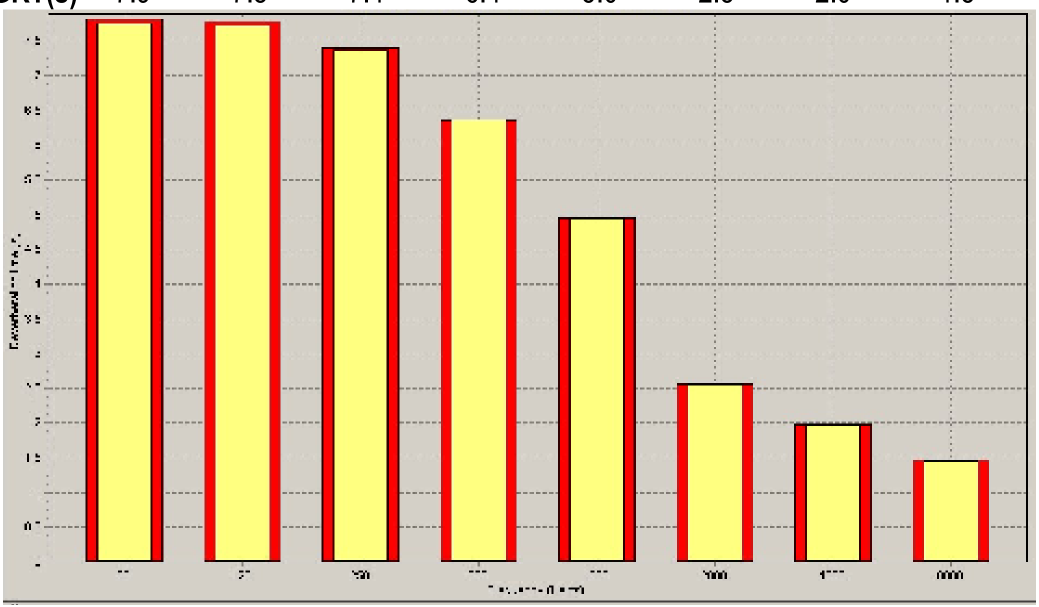

Figure 4.5 Bar chart showing global reverberation times in men's section of Şengül Hamamı between 63 Hz-8000 Hz for AS-IS case, (red color represents "T_{20}", yellow color represents "T_{30}")

4.2.3 REPAIR Case of Şengül Hamamı

Acoustical parameters under unoccupied condition of building, at the specified receiver location for REPAIR case, were given in Table 4.4 in order to summarize five basic parameters in Şengül Hamamı women's and men's sections. The global reverberation time (GRT) of the Şengül Hamamı representative of the whole space, in women's section for the REPAIR case were found to vary in the range of 1.5 s and 4.9 s in the frequencies of 1/1 octave bands (Figure 4.6). The GRT at 500Hz and 1000Hz were found to be 1.5 s and 4.9 s, respectively, with an average GRT of 3.3 s. at mid-frequency (Figure 4.6). On the other hand for the Şengül Hamamı men's section was found to vary in the range of 1.4 s and 4.5 s (Figure 4.7)., and the GRT at 500Hz and 1000Hz were found to be 3.7 s and 1.7 s, respectively, with an average GRT of 2.7 s. at mid-frequency(Figure 4.7).

According to these results, the point RT values at 500 Hz and 1000 Hz, were found to be 3.8 s and 2.6 s, with an average RT value of 3.2 s at mid-frequency in Şengül Hamamı women's section respectively. The point RT values at 500 Hz and 1000 Hz were found to be 3.8 s and 1.4 s, with an average RT value of 2.6 s at mid-frequency in Şengül Hamamı men's section respectively (Table 4.5).

EDT values were found to be 3.3 s at 500 Hz and 2.3 s, at 1000 Hz, in women's section. These values were 1.3 s and 4.1 s, at 500 Hz and 1000 Hz, in men's section respectively. The average values of women's and men's sections were found to be 1.6 s and 2.8 s, respectively, for mid-frequencies (Table 4.5) at the specified receiver location.

f (Hz)	63	125	250	500	1000	2000	4000	8000
GRT(s)	4.9	4.9	4.8	3.9	2.6	2.5	2.0	1.5

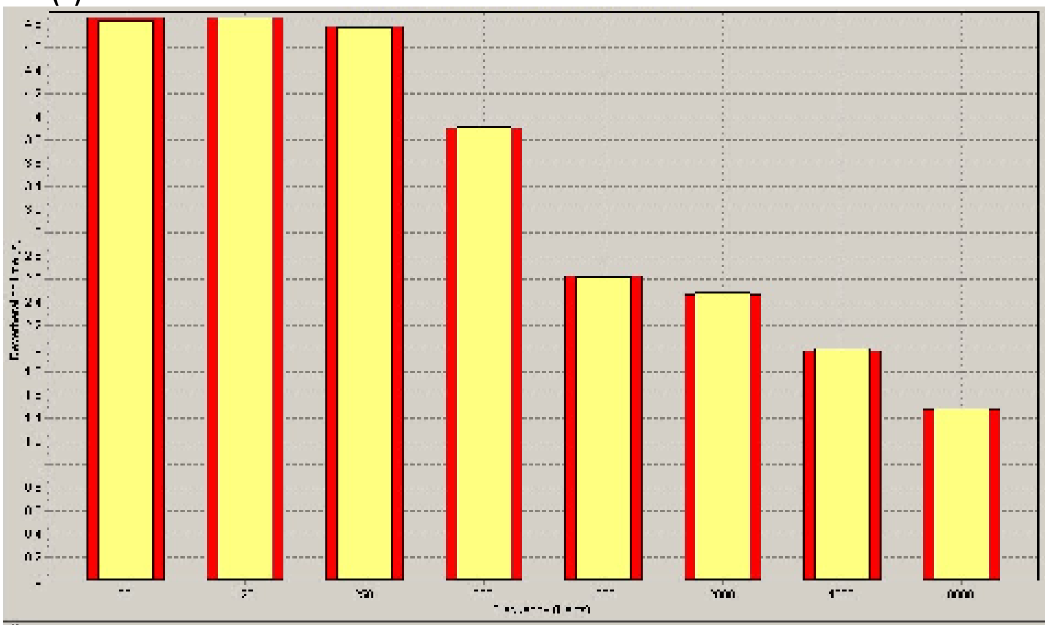

Figure 4.6 Bar chart showing global reverberation times in women's section of Şengül Hamamı between 63 Hz-8000 Hz for REPAIR case, (red color represents "T_{20}", yellow color represents "T_{30}")

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f (Hz)	63	125	250	500	1000	2000	4000	8000
GRT(s)	4.5	4.3	3.9	3.7	1.7	2.2	1.8	1.4

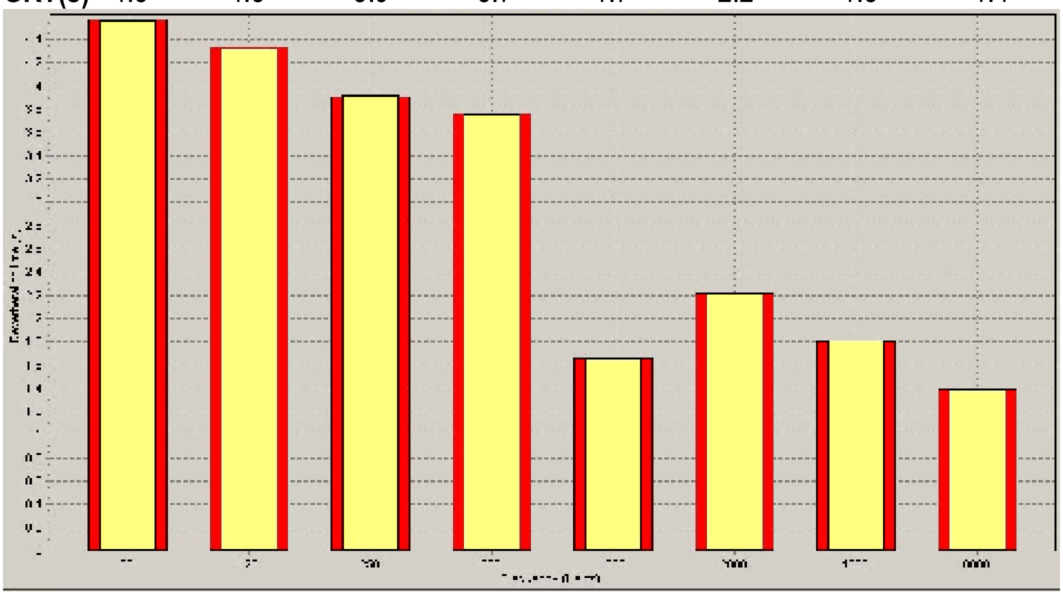

Figure 4.7 Bar chart showing global reverberation times in men's section of Şengül Hamamı between 63 Hz-8000 Hz for REPAIR case, (red color represents "T_{20}", yellow color represents "T_{30}")

.Table 4.5 Results of RT, EDT, C80, LF80, STI values at 500 Hz and 1000Hz at the specified receiver location for the women's & men's sections of Şengül Hamamı calculated for the REPAIR case under unoccupied conditions, and the average of values taken at 500 and 1000 Hz.

Acoustical Parameters	Şengül Hamamı Women's Section REPAIR Case			Şengül Hamamı Men's Section REPAIR Case		
	Frequency			Frequency		
	500	1000	Average	500	1000	Average
RT, s	3.8	2.6	3.2	3.8	1.4	2.6
EDT, s	3.3	2.3	2.8	3.5	1.6	2.6
LF80	0.270	0.265	0.268	0.305	0.317	0.311
C80, dB	-4.3	-2.3	-3.3	-4	0.5	-1.8
STI	0.38			0.40		
Volume, m^3	714			508		

According to Table 4.5, LF80 of the women's section at 500 Hz and 1000 Hz were found to be 0.270 and 265, with average values of 0.268 and LF80 values of men's section, in the building, was found to be 0.305 and 0.317, at 500 Hz and 1000 Hz, and the average values for mid-frequencies (500 Hz and 1000 Hz) were found to be 0.311 respectively at the specified receiver location (Table 4.5).

C80 values for women's section were found be -4.3 dB at 500 Hz and -2.3 dB at 1000 Hz respectively, -3.3 dB as average of mid-frequencies at the specified receiver location. In the men's section C80 values were found be -4 dB at 500 Hz and -0.5 dB at 1000 Hz, the average value for mid-frequencies were found to be -1.8 dB at the specified receiver location (Table 4.5).

According to the Table 4.5, STI value of the Şengül Hamamı women's section was found to be 0.38, and STI value of the Şengül Hamamı men's section was found to be 0.40 at the specified receiver location.

4.3 Acoustical Features of Kadı Hamamı

After determining the sound absorption coefficients of historical lime plaster original acoustical conditions of old Turkish baths were defined by the help of acoustical modeling. In this part, under this heading, ORIGINAL*,* AS-IS and also REPAIR cases were identified for Kadı Hamamı.

4.3.1 ORIGINAL Case of Kadı Hamamı

The global reverberation time (GRT) of the Kadı Hamamı were found to vary in the range of 1.3 s and 5.1 s in the frequencies of 1/1 octave bands (Figure 4.8). The GRT at 500Hz and 1000Hz were found to be 3.3 s and 1.8 s, respectively, with an average GRT of 2.6 s. at mid-frequency (Figure 4.8).

The point RT , EDT, LF80, C80 and STI values at mid-frequencies obtained for the specified receiver location in Kadı Hamamı for the ORIGINAL case were summarized in Table 4.6. According to these results, the point RT values at 500 Hz and 1000 Hz were found to be 3.2 s and 2.0 s, respectively, with an average RT value of 2.6 s at mid-frequency (Table 4.6).

EDT values in Kadı Hamamı were found to be 2.8 s and 1.3 s, in 500 Hz and 1000 Hz, respectively, and 2.1s for average of those values taken at 500 and 1000 Hz for ORIGINAL case at the specified receiver location (Table 4.6).

LF80 values of the Kadı Hamamı were found to be 0.340 and 0.366, at 500 Hz and 1000 Hz respectively, and 0.350 for an average of those values taken at 500 and 1000 Hz at the specified receiver location (Table 4.6).

f (Hz)	63	125	250	500	1000	2000	4000	8000
GRT(s)	5.1	4.7	4.1	3.3	1.8	1.9	1.6	1.3

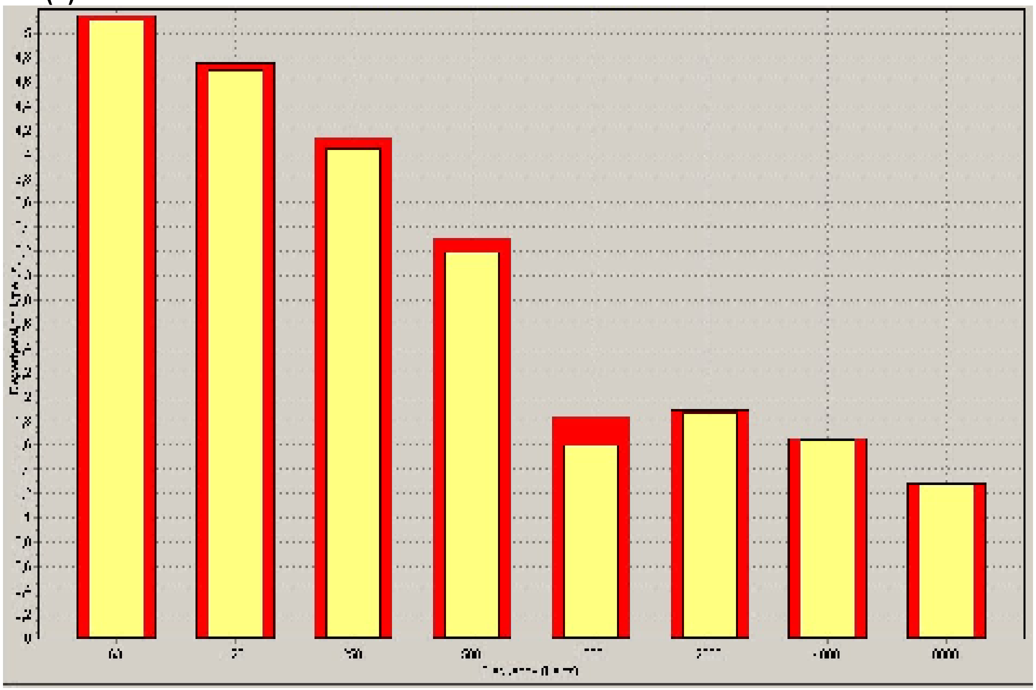

Figure 4.8 Bar chart showing global reverberation times in Kadı Hamamı between 63 Hz-8000 Hz for ORIGINAL case, (red color represents “T_{20}”, yellow color represents “T_{30}”)

.

Table 4.6 Results of RT, EDT, C80, LF80, STI values at 500 Hz and 1000 Hz for the Kadı Hamamı calculated for the ORIGINAL case under unoccupied conditions at the specified receiver location.

Acoustical Parameters	Kadı Hamamı ORIGINAL Case Frequency		
	500	1000	Average
RT, s	3.2	2	2.6
EDT, s	2.8	1.3	2.1
LF80	0.340	0.366	0.353
C80, dB	-3.2	2.7	-0.3
STI	0.41		
Volume, m³	2000		

C80 values of the Kadı Hamamı were found to be -3.2 dB and 2.7 dB, at 500 Hz and 1000 Hz respectively, and -0.3 dB for average of those values of mid-frequency at the specified receiver location (Table 4.6).

According to Table 4.6, STI values of the Kadı Hamamı were determined to be 0.41 at the specified receiver location.

4.3.2 AS-IS Case of Kadı Hamamı

All these parameter results which were taken from ODEON, acoustics computer software, were shown below in sequence for defining the present situation by taking the recent incompatible repairs into consideration. The results obtained from the analyses of AS-IS case were summarized in Table 4.7.

The global reverberation time (GRT) of the Kadı Hamamı were found to vary in the range of 1.8 s and 18.2 s in the frequencies of 1/1 octave bands (Figure 4.8). The GRT at 500Hz and 1000Hz were found to be 10.5 s and 6.3 s, respectively, with an average GRT of 8.4 s. at mid-frequency (Figure 4.9). According to, the point RT values at 500 Hz and 1000 Hz were found to be 10.4 s and 6.2 s, with an average RT value of 8.3 s at mid-frequency in Kadı Hamamı respectively at the specified receiver location (Table 4.7).

As seen in Table 4.7, EDT values were observed to be 10.6 s and 6.3 s, at 500 Hz and 1000 Hz, respectively. The average values of the Kadı Hamamı were found to be 8.5 s in mid-frequencies (500 Hz and 1000 Hz) under unoccupied conditions of inside at the specified receiver location. According to results, it can be said that EDT was observed to have the higher values than RT values of Kadı Hamamı. It means that if the RT is shorter than EDT, the sense of reverberation can become subjectively inadequate. In other words if the RT becomes longer than the recommended maximum of 2.2s, like in this case (RT belongs to 10.4- 6.2s with averga of the 8.3s values), EDT would be longer than RT values (Barron, 1998).

According to Table 4.7, LF80 values of the Kadı Hamamı were found to be 0.346 and 0.365, at 500 Hz and 1000 Hz, and 0.346 for average values of 500 Hz and 1000 Hz for AS-IS case under unoccupied conditions at the specified receiver location.

C80 values of the Kadı Hamamı were found to be -9.4 dB and -7 dB, at 500 Hz and 1000 Hz respectively, and -8.2 dB for average of those values of mid-frequency at the specified receiver location (Table 4.7). According to Table 4.7, STI values of the Kadı Hamamı at the specified receiver location were determined to be 0.25 which is the lowest value among the all cases (Table 4.7).

f (Hz)	63	125	250	500	1000	2000	4000	8000
GRT(s)	18.2	17.9	14.7	10.5	6.3	3.6	2.4	1.8

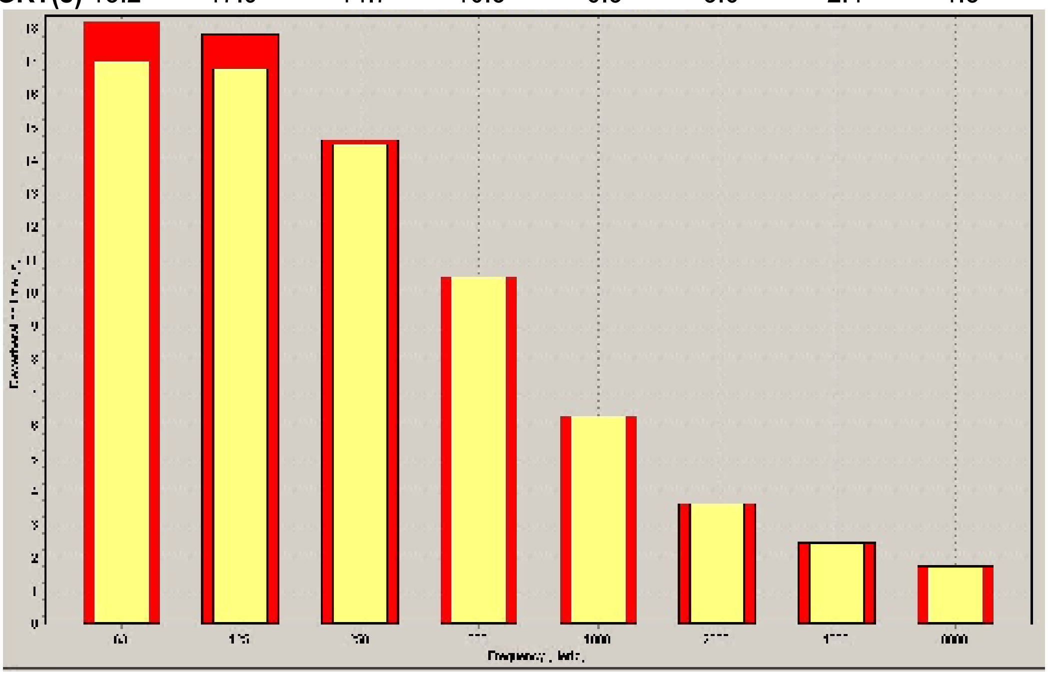

Figure 4.9 Bar chart showing global reverberation times in Kadı Hamamı between 63 Hz-8000 Hz for *AS-IS* case, (red color represents "T_{20}", yellow color represents "T_{30}")

Table 4.7 Results of RT, EDT, C80, LF80, STI values at 500 Hz and 1000Hz for the Kadı Hamamı calculated for the AS-IS case under unoccupied conditions, and the average of those values taken at 500 and 1000 Hz at the specified receiver location.

Acoustical Parameters	Kadı Hamamı AS-IS Case		
	Frequency		
	500	1000	Average
T30, s	10.4	6.2	8.3
EDT, s	10.6	6.3	8.5
LF80	0.346	0.345	0.346
C80, dB	-9.4	-7	-8.2
STI	0.25		
Volume, m^3	2000		

4.3.3 REPAIR Case of Kadı Hamamı

The global reverberation time values of the Kadı Hamamı for the REPAIR case were found to vary in the range of 1 s and 3.9 s in the frequencies of 1/1 octave bands (Figure 4.10). At mid-frequency, the GRT at 500Hz and 1000Hz were found to be 1.7 s and 3.9 s, respectively, with an average GRT of 2.8 s.

The RT, EDT, LF80, C80 and STI values at mid-frequencies obtained for the specified receiver location in Kadı Hamamı for the REPAIR case were summarized in Table 4.8. According to results, the point RT values at 500 Hz and 1000 Hz were found to be 2.0 s and 3.9 s, respectively, with an average RT value of 3 s at mid-frequency.

The EDT values at 500 Hz and 1000 Hz were found to be 1.8 s and 3.9 s, respectively with an average EDT of 2.8 s at mid-frequency. The LF80 values were found to be 0.258 and 0.274, at 500 Hz and 1000 Hz respectively, and 0.266 for an average of those values taken at 500 and 1000 Hz (Table 4.8).

f (Hz)	63	125	250	500	1000	2000	4000	8000
GRT(s)	3.3	2.9	2.3	1.7	3.9	1.2	1.2	1.0

Figure 4.10 Bar chart showing global reverberation times in Kadı Hamamı between 63 Hz-8000 Hz for REPAIR case, (red color represents “T_{20}”, yellow color represents “T_{30}”)

.

Table 4.8 Results of RT, EDT, C80, LF80, STI values at 500 Hz and 1000Hz for the Kadı Hamamı calculated for the REPAIR case under unoccupied conditions at the specified receiver location.

Acoustical Parameters	Kadı Hamamı REPAIR Case Frequency		
	500	1000	Average
RT, s	2	3.9	3
EDT, s	1.8	3.9	2.8
LF80	0.258	0.274	0.266
C80, dB	0.1	-4.4	-2.2
STI	0.45		
Volume, m^3	2000		

C80 values of Kadı Hamamı were found to be -0.1dB and -4.4dB, at 500 Hz and 1000 Hz, and -2.2 dB with an average of 500 and 1000 Hz respectively (Table 4.8). According to Table 4.7, STI value of Kadı Hamamı was found to be 0.45 for REPAIR case of unoccupied condition of inside at the specified receiver location.

4.4 Comparison of ORIGINAL and AS-IS Cases

In this section, it was aimed to illustrate the distribution graphs of Turkish baths given in sequence and subsequent to the acoustical modeling of the structures, and to point out how inappropriate renovations affect the original acoustical characteristics, and to represent deteriorations in acoustics within the structures as the years went by. In the context of the study, processed data was displayed with the comparison of ORIGINAL and AS-IS case, by the help of graphs. Comparison was done by taking acoustical parameters individually.

4.4.1 Reverberation Time

Under the this heading, acoustical conditions of ORIGINAL case and AS-IS case were compared with each other in terms of RT, in order to show the differences between past and present time effect on the acoustical ambiance of historical Turkish baths. The maps showing the distribution of RT values shown in this section as graphs for Şengül Hamamı women's and men's sections, and also Kadı Hamamı under unoccupied conditions, respectively.

At the specified receiver location the results of RT at frequencies from 63 Hz to 2000 Hz were given in Figure 4.11. It was seen that great differences between ORIGINAL case and AS-IS case were observed. For these two Turkish baths considered in the study, maximum RT was appeared at 63 Hz and minimum 2000 Hz for ORIGINAL case, while maximum RT at 125 Hz, and minimum RT was appeared at 2000 Hz, for AS-IS case. RT values of ORIGINAL and AS-IS cases generally showed higher value at 500 Hz than at 1000 regarding mid frequencies. Different types of materials (Figure 4.1) used in structures should create different values of RT, since they have great difference in sound absorption coefficients. The maps showing the distribution of RT values shown in Figures 4.12-4.14 showed that the RT increases at the positions getting far away from the specified sound source location, which was on the elevated platform in caldarium.

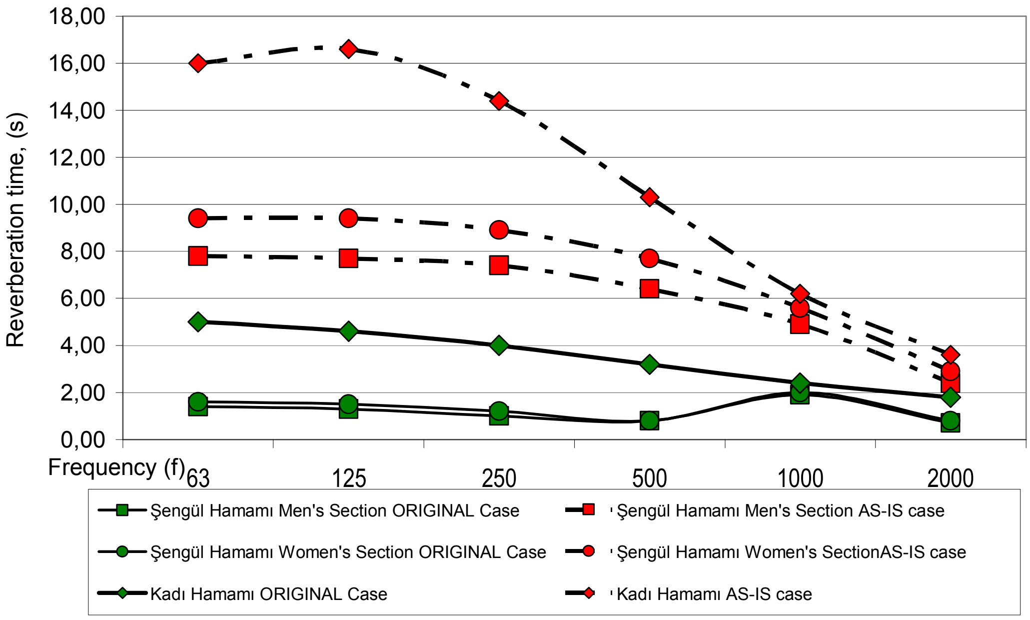

Figure.4.11 The *RT* curves of Şengül Hamamı men's and women's sections and Kadı Hamamı, calculated for ORIGINAL and AS-IS cases in unoccupied conditions, at the specified receiver location, versus the frequencies between 63 Hz and 2000 Hz.

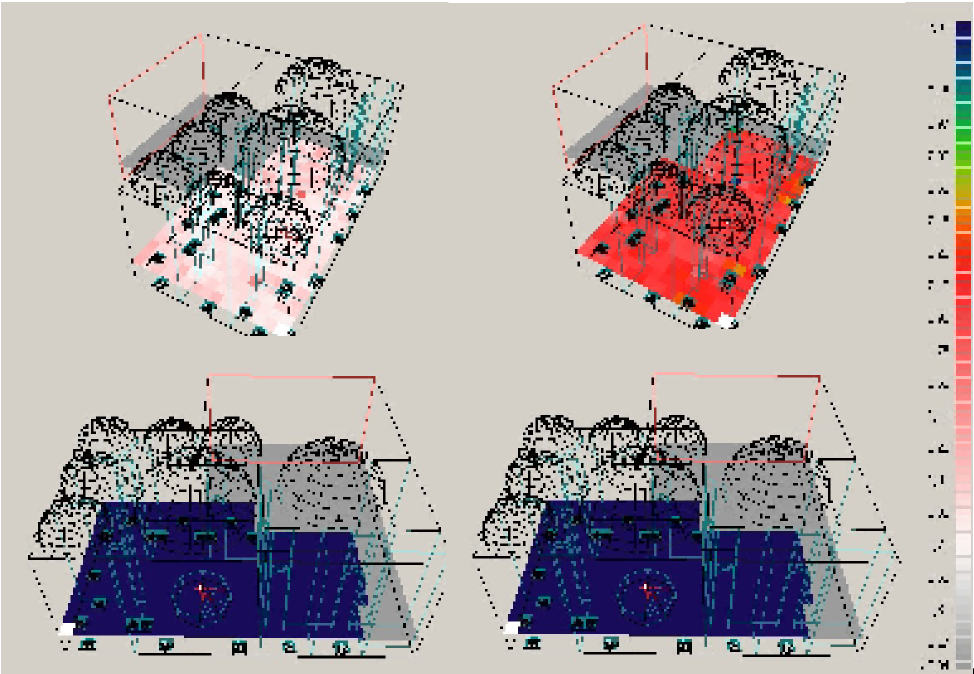

Figure 4.12 The graph showing the T30 distribution at 500 Hz (left) and 1000 Hz (right) for ORIGINAL case (above) and AS-IS case (below), in Şengül Hamamı women's section.

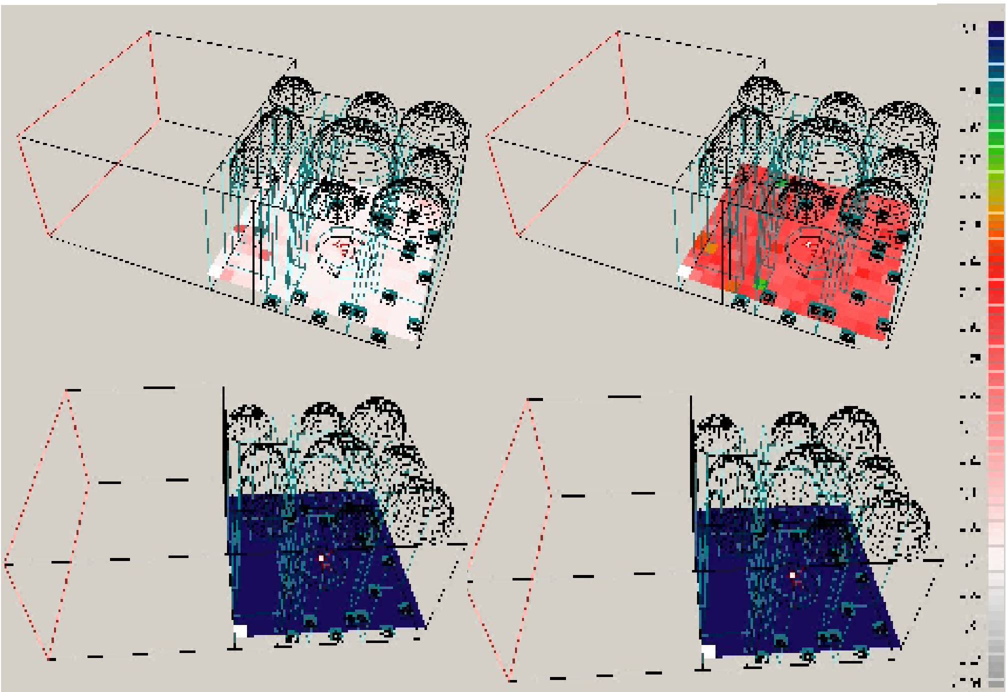

Figure 4.13 The graph showing T30 distribution at 500 Hz (left) and 1000 Hz (right) for ORIGINAL case (above) and AS-IS case (below), in Şengül Hamamı men's section

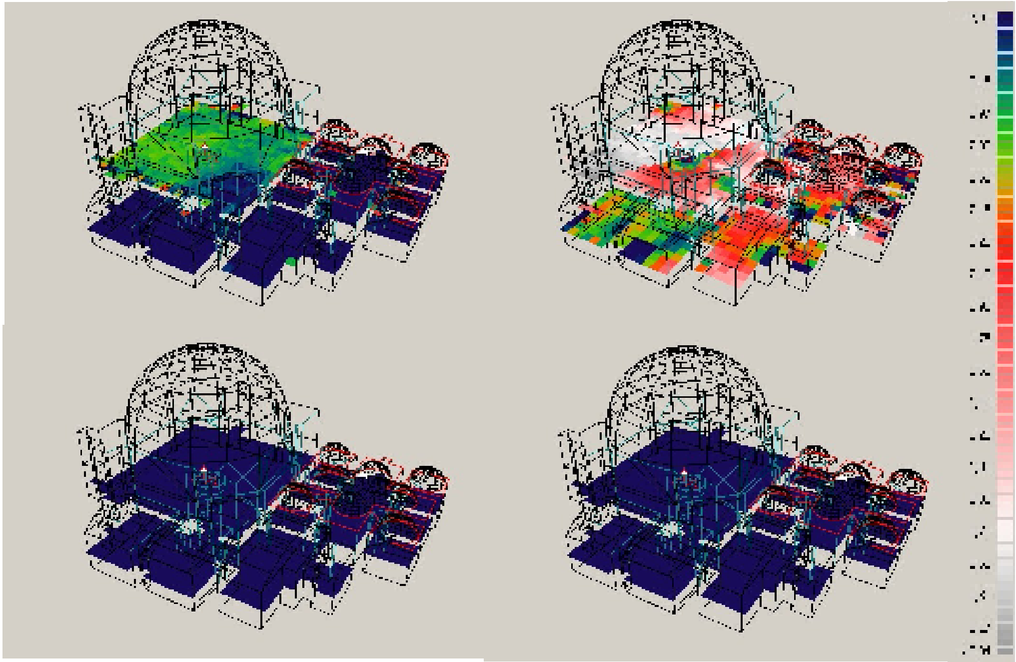

Figure 4.14 The graph showing T30 distribution at 500 Hz (left) and 1000 Hz (right) for ORIGINAL case(above) and AS-IS case(below graphs), in Kadı Hamamı.

It was important both speech and musical performances in order to define the range of different spaces by considering occupied condition of speech, speech & music and only music activities of the average mid frequency (500 Hz and 1000 Hz). As explained in literature survey part, optimum RT values were shown in Figure 4.15. In the graph, ordinate shows only speech, speech and music, only music activities, in the 1/1 frequency bandwidth, the apses shows optimum RT in seconds which is obtained experimentally in time for number of different activities in the range of 500 Hz and 1000 Hz. Figure 4.15 is courtesy of Egan (1972) and it was presented before, in chapter 2 (Figure 2.5).According to graph RT (Figure 4.15) values of two buildings were comparable with values of churches. In fact geometrical form of both building churches and Turkish baths are similar. After determining optimum RT values for historical Turkish baths which were obtained by this study, they were added on this graph (blue line), in order to display the expanded various activities.

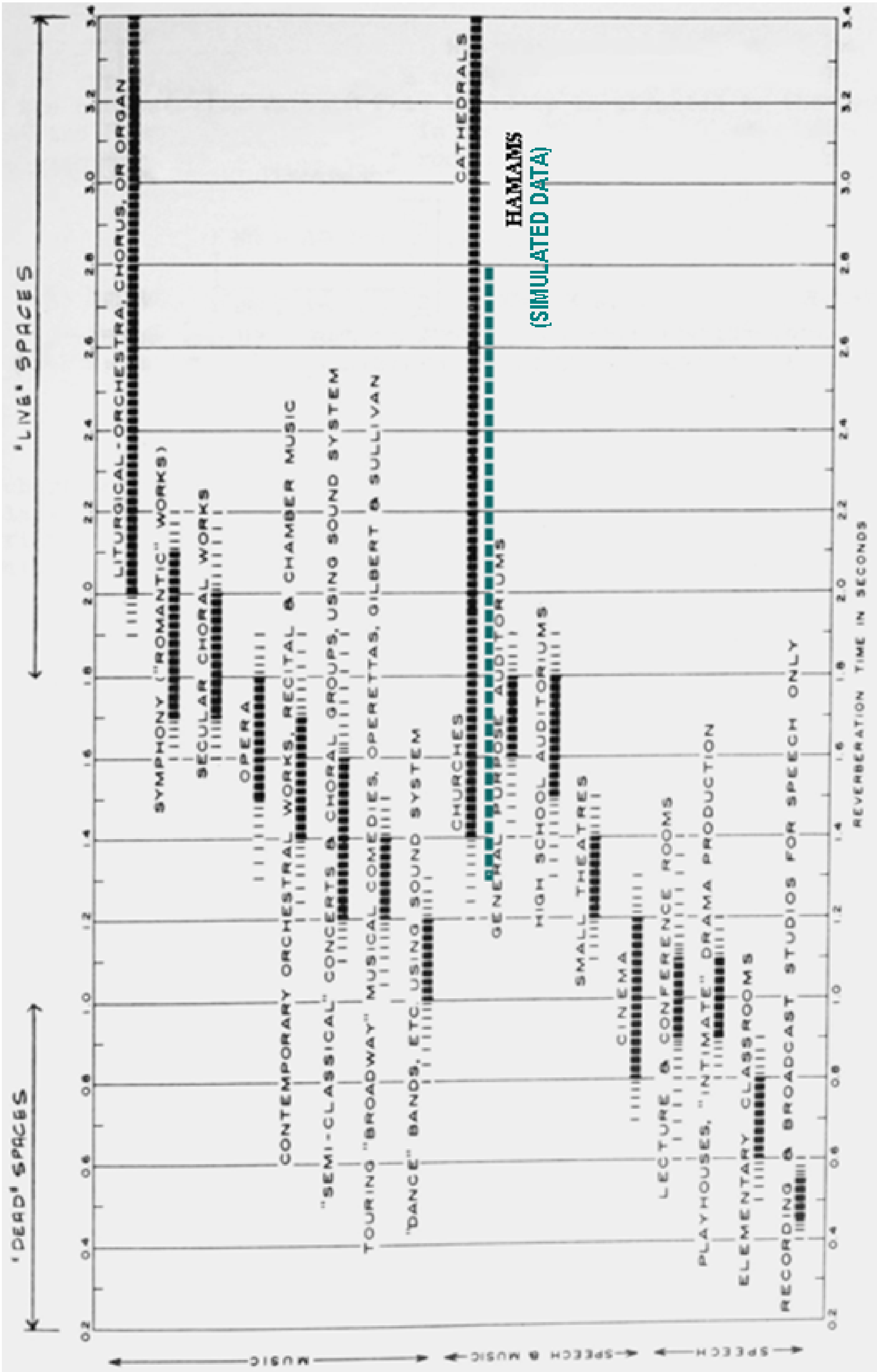

Figure 4.15 The graph showing to optimum RT values at 500-1000 Hz for speech, speech& music and only music activities for different facilities including the RT values of the Historical Turkish Bath structures (blue line-Simulated data)

(Egan, 1972).

4.4.2 Early decay Time EDT

The EDT parameter was represented in Figures 4.16-4.19. The results of the simulations were presented for Şengül Hamamı women's section, men's section and Kadı Hamamı, respectively, depending on their interior surface materials and geometrical and volume conditions. In order to illustrate the efficiency and the compatibility of the buildings, in terms of EDT, two major cases were simulated and evaluated for each Turkish bath.

The application of historical lime plaster was found to make the acoustics properties of inside better (Figure 4.2). For ORIGINAL case, EDT values were found to be in the range of 0.6 s and 4.9 s(Figure 4.18 to 4.19). According to the EDT graph, Figure 4.16, EDT values of AS-IS case, individually, were found to be high values varying in a wide range of 16.5 s and 2.3 s with an average value of being 7.9 s. In other words, AS-IS cases of structures were determined as the highest EDT values, while ORIGINAL cases of Turkish baths were determined as the lowest EDT values. On the other hand, in the AS-IS case of EDT, it was observed to have the higher values than RT values of AS-IS case (Figure 4.11). In other words, EDT values were longer than RT values. That means, EDT and RT values were coherent with each other in ORIGINAL case but not coherent in AS-IS case.

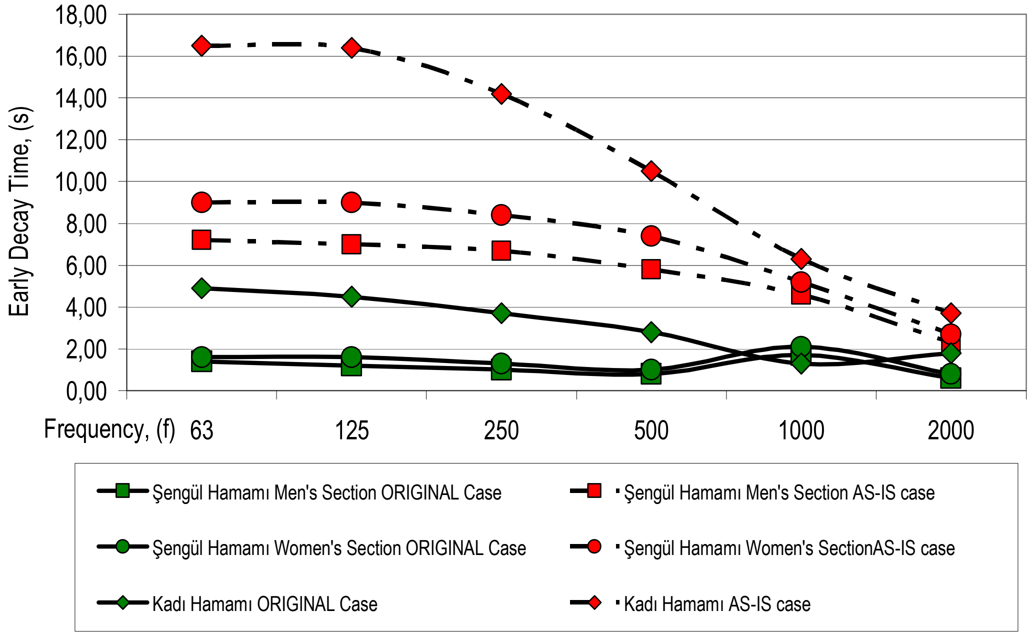

Figure.4.16 The EDT curves of Şengül Hamamı men's and women's sections and Kadı Hamamı, calculated for ORIGINAL and AS-IS cases under unoccupied conditions, at the specified receiver location, versus the frequencies between 63 Hz and 2000 Hz.

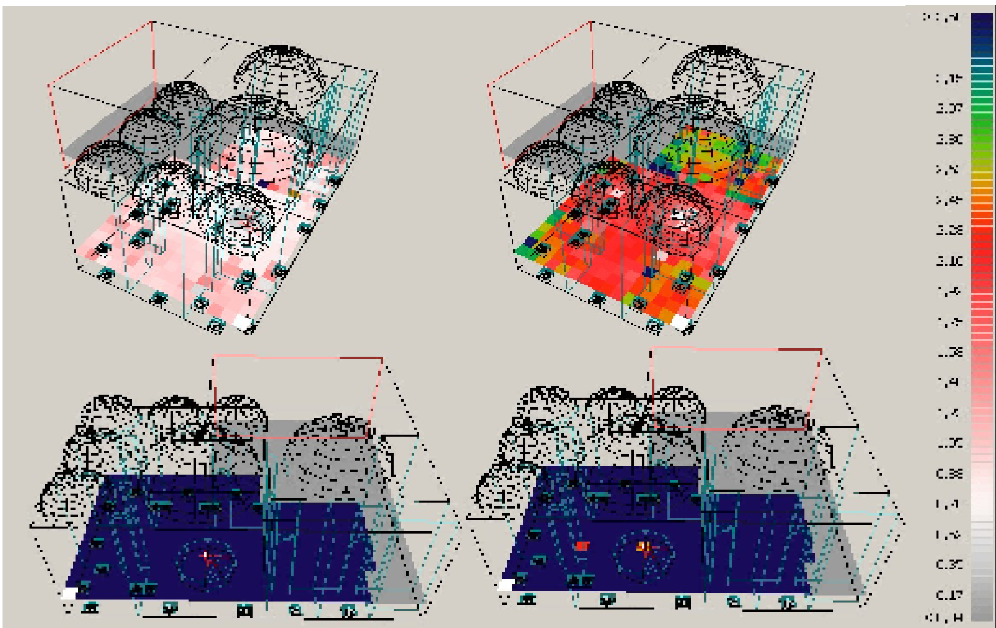

Figure 4.17 The graph showing the EDT distribution at 500 Hz (left) and 1000 Hz (right) for ORIGINAL case (above) and AS-IS case (below), in Şengül Hamamı women's section.

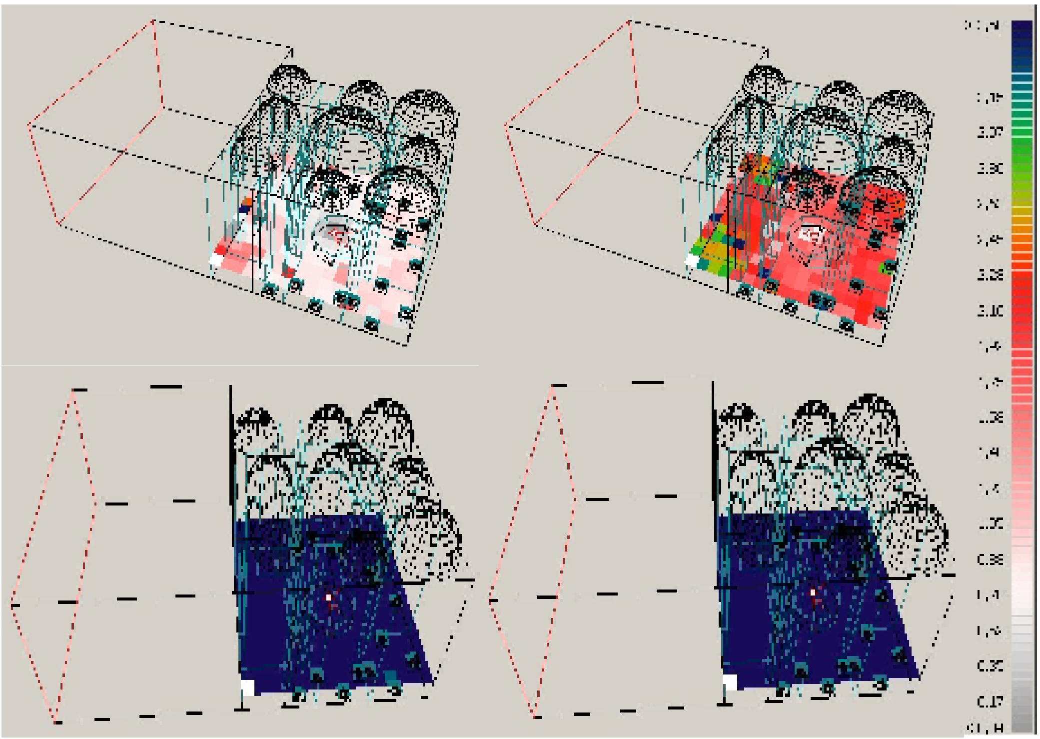

Figure 4.18 The graph showing the EDT distribution at 500 Hz (left)-1000 Hz (right) for ORIGINAL case (above) and AS-IS case (below), in Şengül Hamamı men’s section.

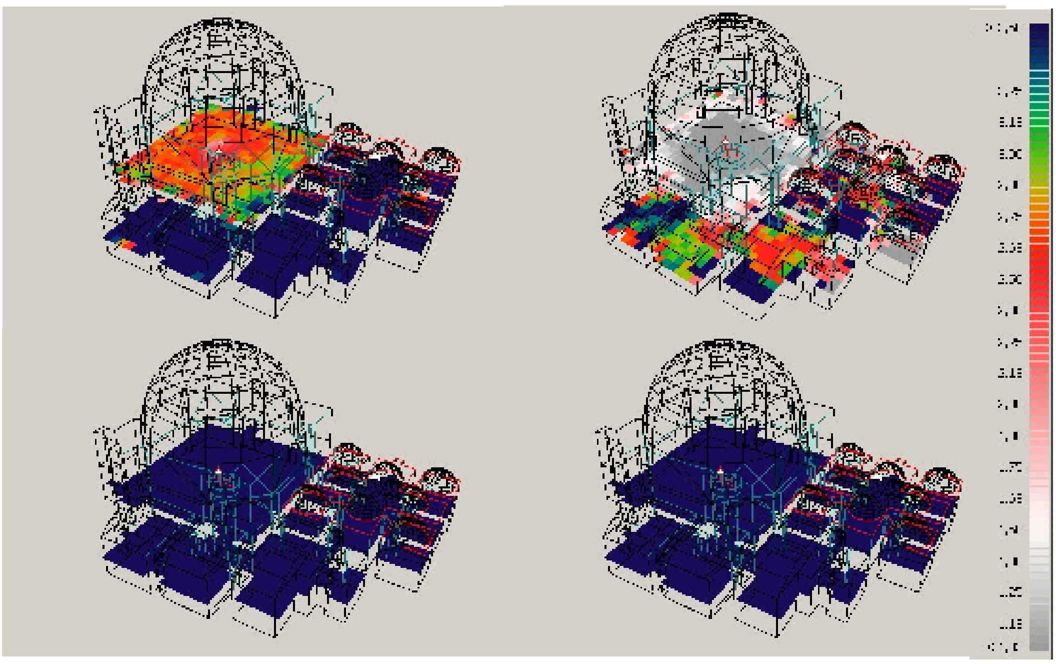

Figure 4.19 The graph showing the EDT distribution at 500 Hz (left)-1000 Hz (right) for ORIGINAL case(above) and AS-IS case(below graphs), in Kadı Hamamı.

4.4.3 Lateral Fraction LF80

The LF80 of the AS-IS case and ORIGINAL case was observed to be similar to each other as shown in Figure 4.20. Since LF80 values have a relation with the usage of less absorptive materials, as expected LF80 values were detected in satisfaction range, for two cases at the specified receiver location. LF80 in caldarium and tepidarium part of AS-IS case were found to be in the range of 0.252 and 0.347 in the 1/1 frequency bandwidth (Table 4.6), while LF80 values of ORIGINAL case were found to be in the range of 0.196-0.366. To give a general idea of grid response, distribution graph will be helpful (Figures 4.21 to 4.23). It was seen that, similarity to LF80 values of ORIGINAL case was a slightly lower values when compared with AS-IS case.

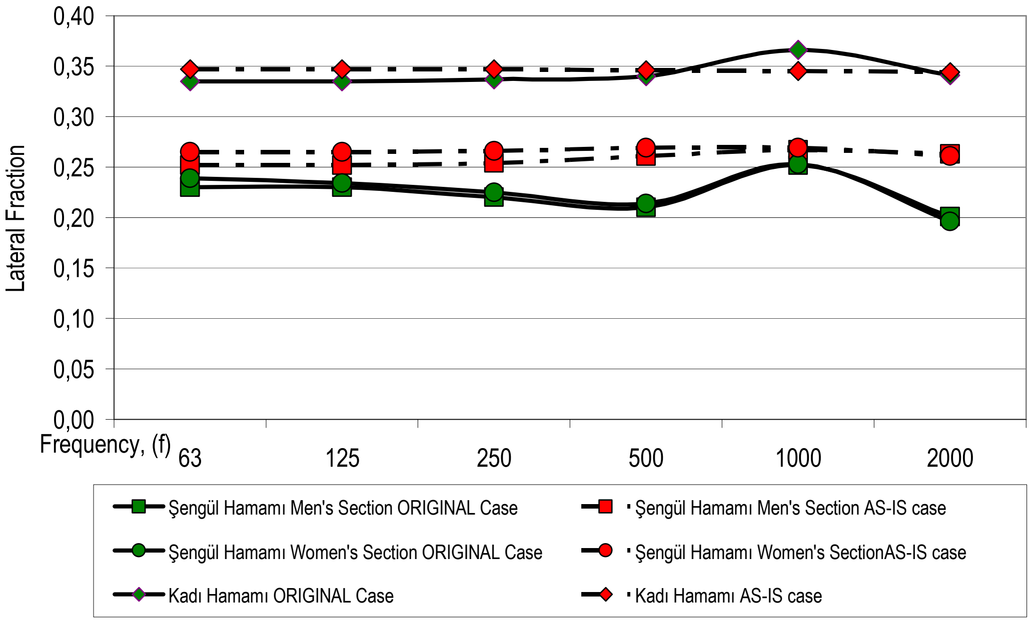

Figure.4.20 The LF80 curves of Şengül Hamamı men's and women's sections and Kadı Hamamı, calculated for ORIGINAL and AS-IS cases under unoccupied conditions, at the specified receiver location versus the frequencies between 63 Hz and 2000 Hz.

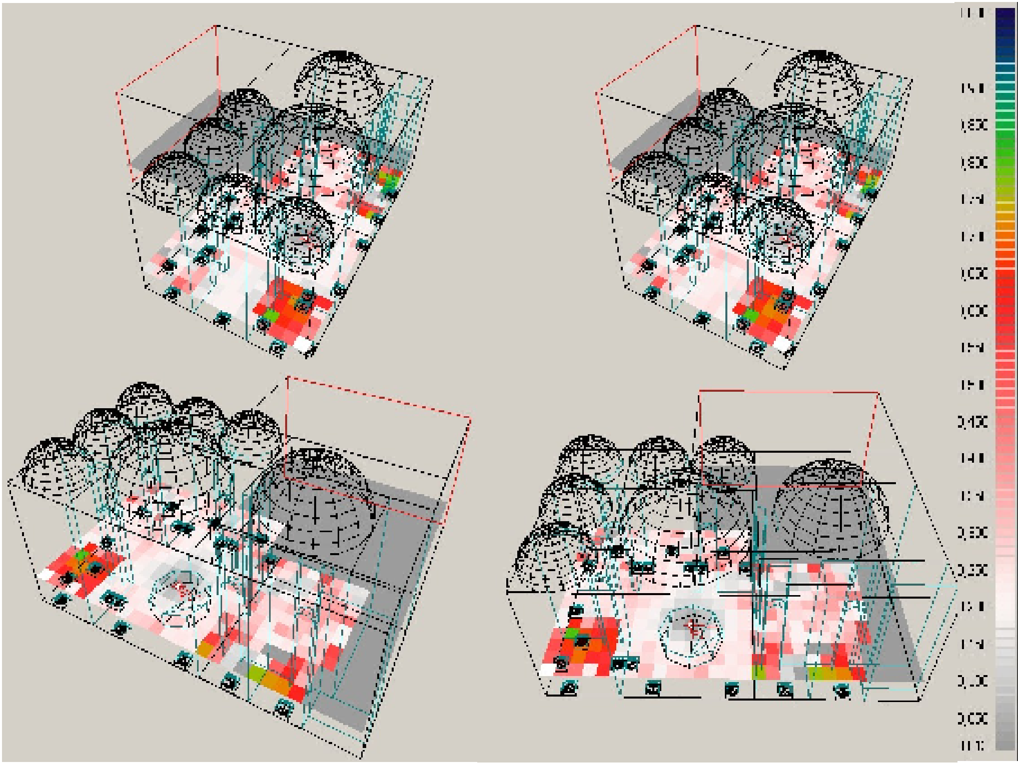

Figure 4.21 The graph showing the LF80 distribution at 500 Hz (left)-1000 Hz (right) for ORIGINAL case (above) and AS-IS case (below), in Şengül Hamamı women's section.

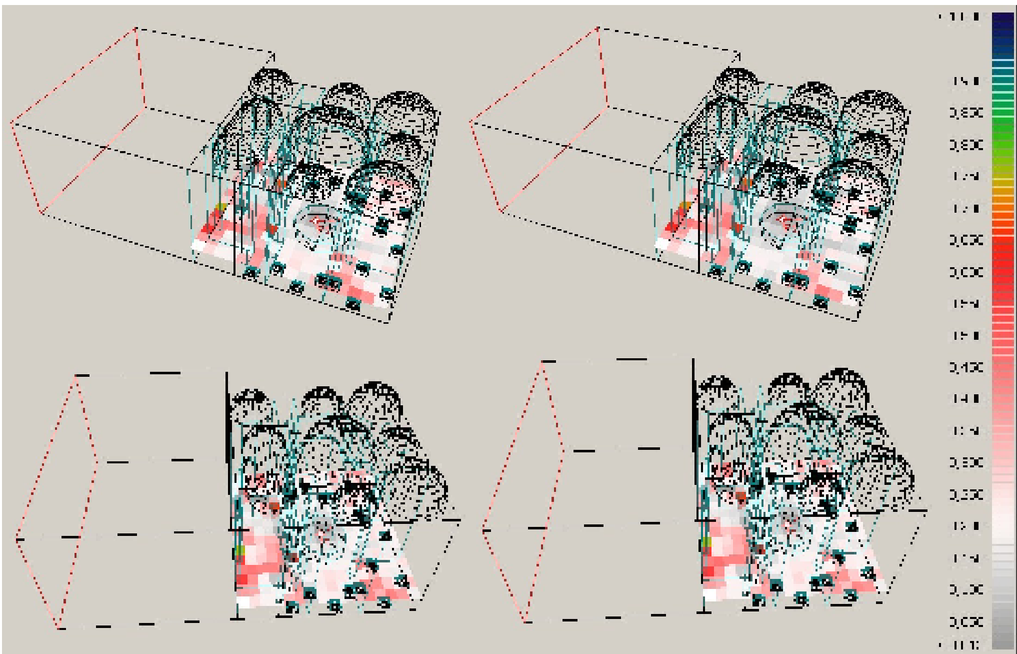

Figure 4.22 The graph showing the LF80 distribution at 500 Hz (left) -1000 Hz (right) for ORIGINAL case (above) and AS-IS case (below), in Şengül Hamamı men's section.

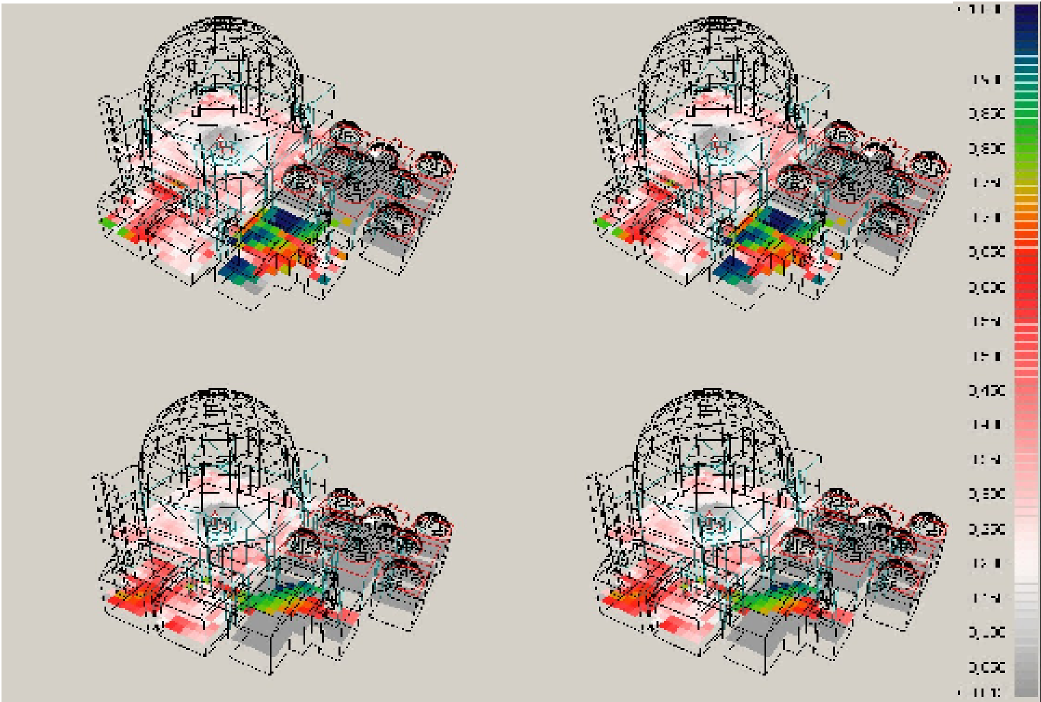

Figure 4.23 The graph showing the LF80 distribution at 500 Hz (left)-1000 Hz (right) for ORIGINAL case(above) and AS-IS case(below graphs), in Kadı Hamamı.

4.4.4 Clarity C80

In the light of findings, (Figure 4.24) at the specified receiver location, C80 values of ORIGINAL case distributed between +7.6 dB and -5.8 dB, while on the opposing, AS-IS case of C80 values distributed -2.1 dB to -11.5 dB which is the latter has worse value according to the former one. This mean C80 values of AS-IS case became worse comparing with ORIGINAL case due to compatible repairs materials used in time. This changing can be more clearly seen in graph representations given in Figures 4.25 to 27. This is also a striking fact, when compared to the ORIGINAL case of structure with the AS-IS case, It can be noticed that in Figures 4.25 to 4.27 indicate, C80 values of AS-IS case, having high negative value, while C80 values of ORIGINAL case showed that in the range of -4 dB to 4 dB, mostly exist in positive values.

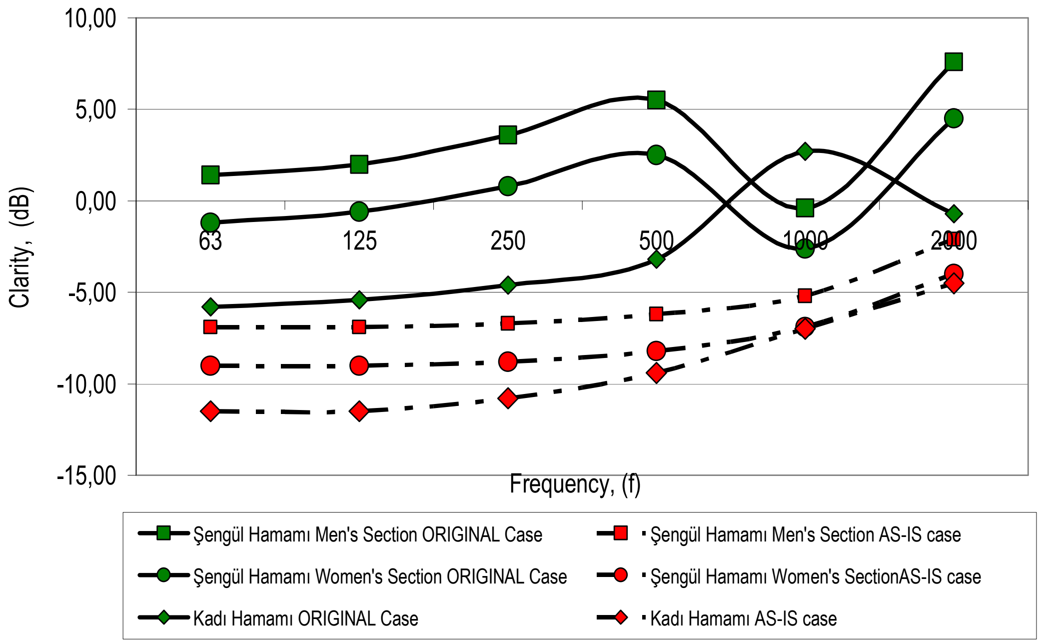

Figure.4.24 The C80 curves of Şengül Hamamı men's and women's sections and Kadı Hamamı, calculated for ORIGINAL and AS-IS cases under unoccupied conditions, at the specified receiver location, versus the frequencies between 63 Hz and 2000 Hz.

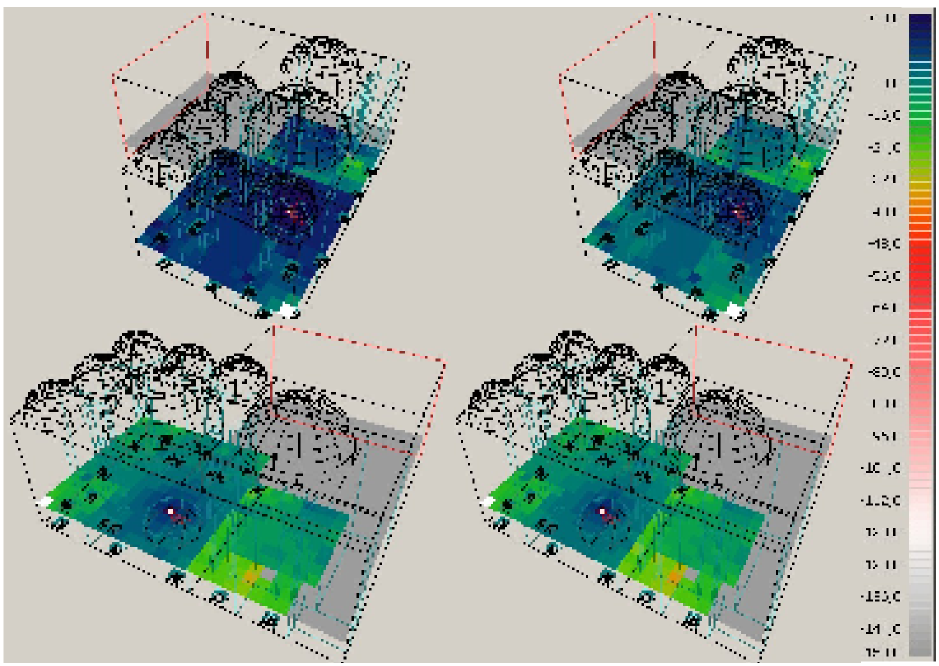

Figure 4.25 The graph showing the C80 distribution at 500 Hz (left) and 1000 Hz (right) for ORIGINAL case (above) and AS-IS case (below), in Şengül Hamamı women's section.

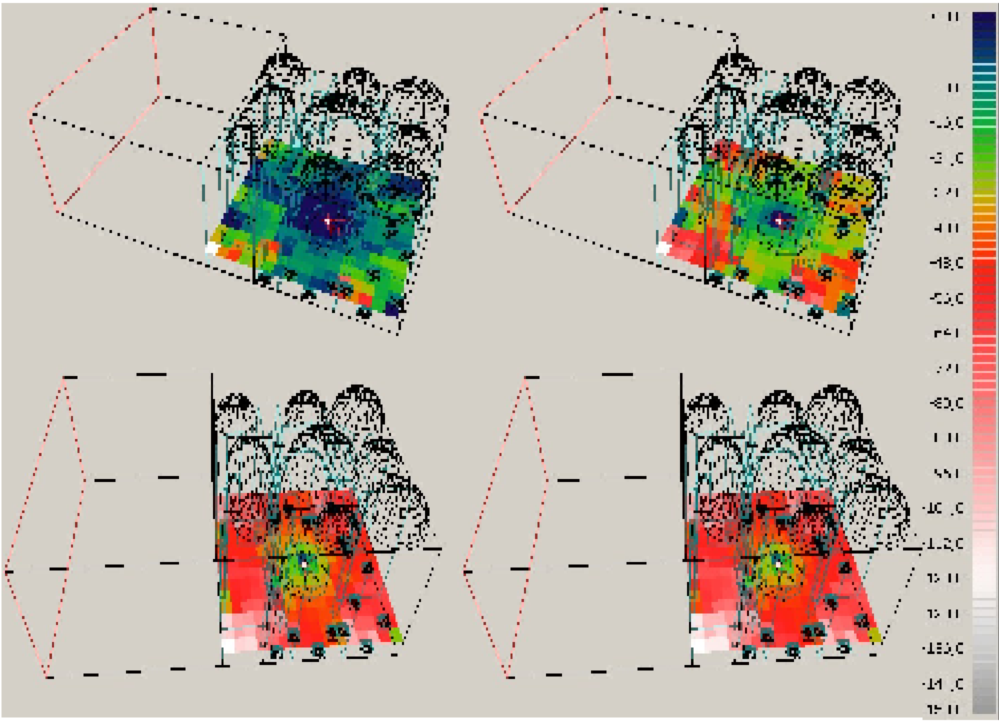

Figure 4.26 The graph showing the C80 distribution at 500 Hz (left)-1000 Hz (right) for ORIGINAL case (above) and AS-IS case (below), in Şengül Hamamı men’s section.

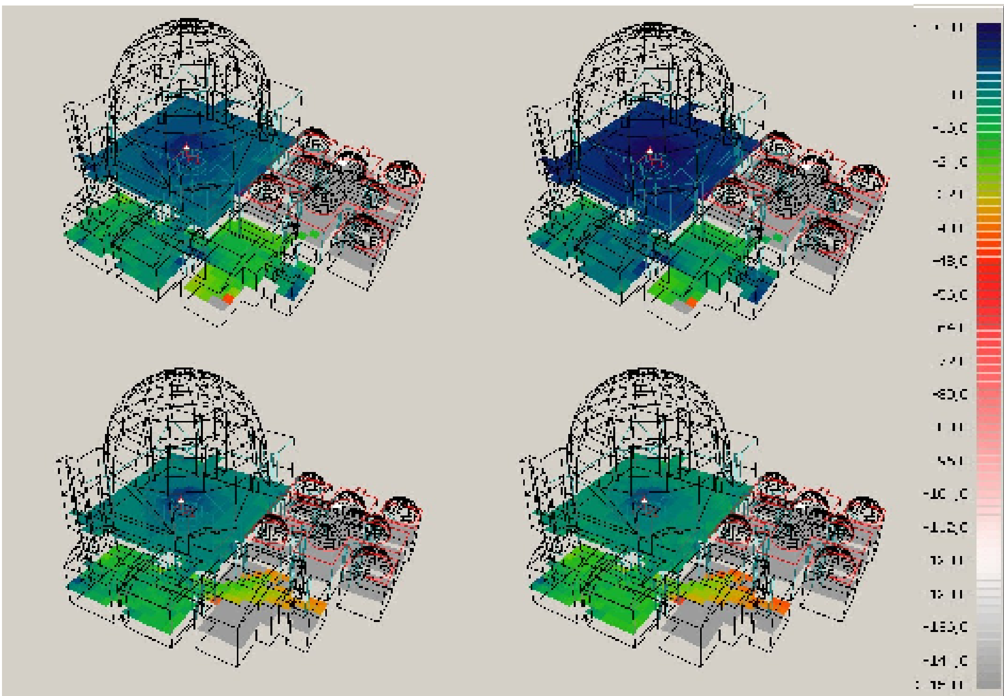

Figure 4.27 The graph showing the C80 distribution at 500 Hz (left) and 1000 Hz (right) for ORIGINAL case(above) and AS-IS case(below graphs), in

Kadı Hamamı

4.4.5 Speech Transmission Index STI

The last evaluation was documented for STI value among the buildings (Figure 4.28). The STI of the ORIGINAL case was found out to lie in range of 0.40-0.63. There is slight decrease in halvet (private room) region (Figure 4.29 to 31),This is because this region was away from sound source, thus it has higher lateral fraction which tends to decrease intelligibility. On the other hand STI values of AS-IS case were found to be in poor range in Figure 4.28. STI values of REPAIR case were found to be better when compared to the values of AS-IS case (Figures 4.28).

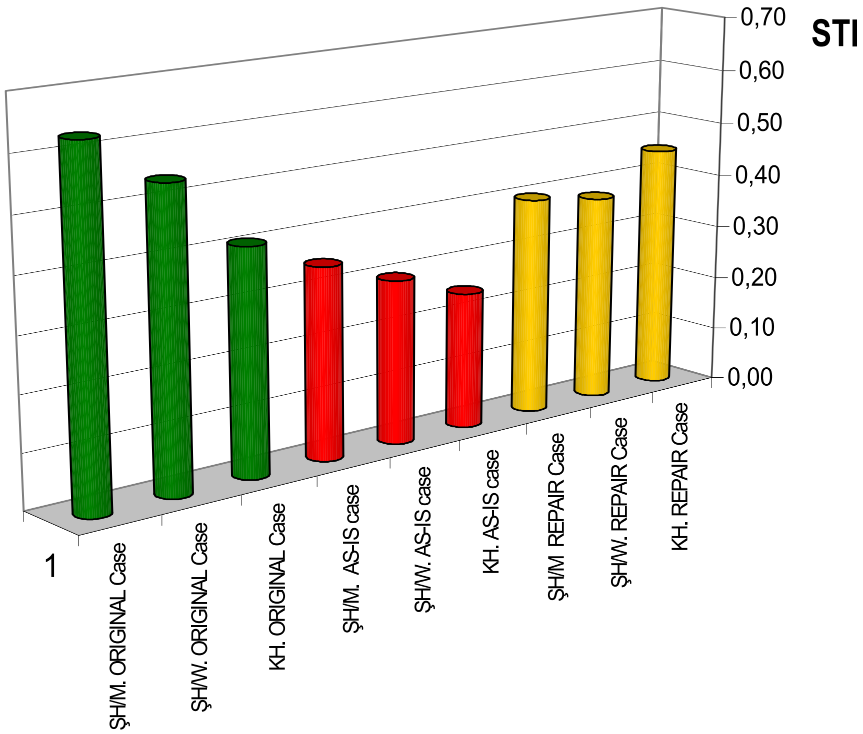

Figure.4.28 The graph showing sound transmission index (STI) values of Şengül Hamamı women's & men's sections and Kadı Hamamı at the specified receiver location for three configurations; ORIGINAL, AS-IS and REPAIR cases.

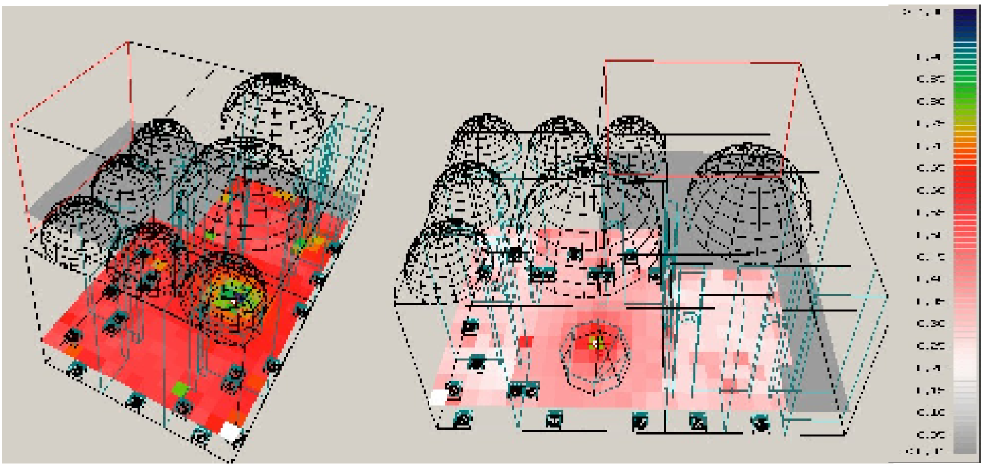

Figure 4.29 The graph showing the STI distribution for ORIGINAL case (left graph) and AS-IS case (right graph), in Şengül Hamamı women's section.

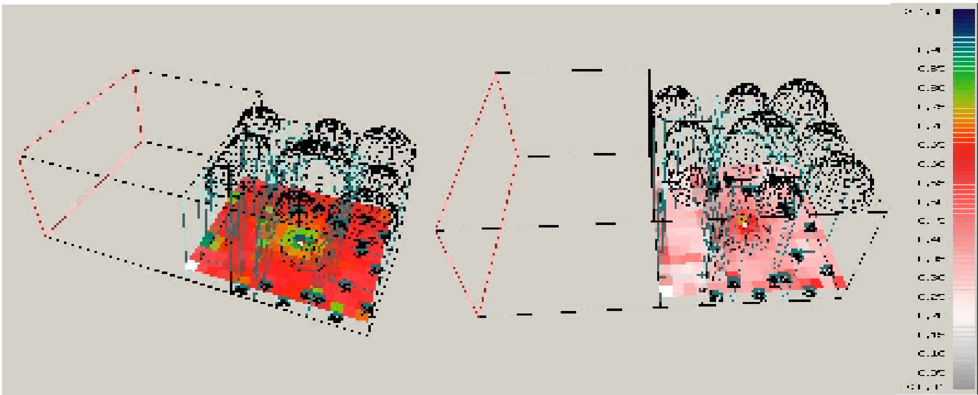

Figure 4.30 The graph showing STI distribution for ORIGINAL case (left) and AS-IS case (right), in Şengül Hamamı men's section.

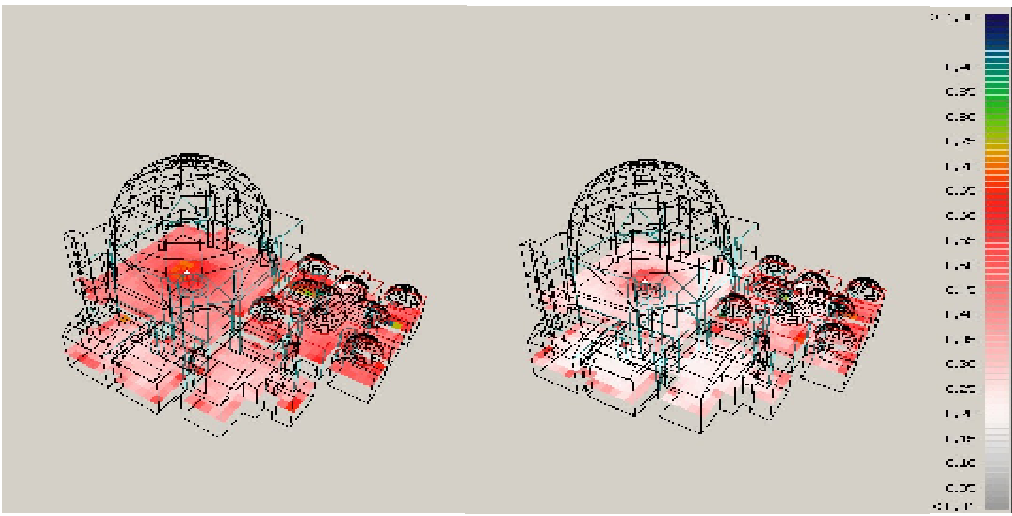

Figure 4.31 The graph showing STI distribution for ORIGINAL case (left) and AS-IS case (right), in Kadı Hamamı.

CHAPTER 5

DISCUSSION AND CONCLUSION

In this chapter the discussions of the study are presented under the titles of "sound absorption characteristics of historical plasters used in historical Turkish baths", "original acoustical features of historical Turkish baths", "the effect of marble-cladding at the lower parts of walls on the original acoustical features" and "the effect of improper recent repairs on the original acoustical features".

Here, the ORIGINAL acoustical features of the historical Turkish baths and changes in those features due to the recent repairs are discussed in terms of basic acoustical parameters: the global reverberation time (GRT) and point values of reverberation time (RT), early decay time (EDT), clarity (C80), lateral fraction.(LF80) and sound transmission index (STI) at the specified receiver location. At the end are given the conclusions followed by suggestion for further studies.

5.1 Sound Absorption Characteristics of Historical Plasters Used in Historical Turkish Baths

The sound absorption coefficient values of dry, damp and wet historical lime plasters obtained at the frequencies of 1/1 octave bands were compared with each other as well as with the other finishing materials used in Şengül Hamamı and Kadı Hamamı (Figure 4.1 and Table 4.2). In the mid-frequency, the sound absorption coefficient of dry sample (α_d) of the historical plaster was 0.23 at 500Hz and 0.29 at 1000Hz with an average value of 0.26. For the damp historical plaster sample, the sound absorption coefficient (α_{85}) was 0.15 at 500Hz and 0.27 at 1000Hz with an average value of 0.21 in mid-frequency. Except for the 500 Hz frequency, the dry and damp samples were observed to have similar sound absorption characteristics. The sound absorption coefficients of dry and damp samples at 2000Hz were found to be higher with the values of 0.32 and 0.34, respectively. These high sound absorption coefficient values, especially at high frequencies, should have contributed to improve the speech intelligibility of spaces. The sound absorption coefficient of wet historical plaster samples (α_{100}), however, was considerably lower than those of dry and damp samples. The α_{100} value was 0.13 at 500Hz and 0.11 at 1000Hz with an average α_{100} value of 0.12 in mid-frequency.

The comparisons of the finishing materials' sound absorption coefficient values at the frequency of 1/1 octave bands showed that the sound absorption coefficient (α) of historical lime plaster layers in all conditions were considerably higher than those of oil-painted cement-based plaster, marble and glass surfaces (Table 4.2 and Figure 4.1). Considering the real moisture content situation of the historical plasters for the *ORIGINAL* case, the historical sample with the average α_{85} value of 0.21, exhibited almost 7 times greater sound absorption capacity than the cement-based one, having an average α of 0.03 at mid-frequency (Cowan, 2000; Egan, 1988; Long, 2006).

It is well known that cement-based materials are incompatible with the historical materials since they introduce dampness and soluble salts problem to the historical structures (Caner, *et al*, 1985; Caner-Saltık, 1991; Kandemir, *et al.*, 2007). By this study, it was confirmed that the contemporary cement-based plaster was incompatible with the porous historical lime plasters in terms of acoustical properties as well. Due to their considerably low sound absorption characteristics cement-based plasters seemed to definitely-destroy the original acoustical features of historical baths inside.

The marble surfaces, as original flooring of historical Turkish baths, and the bell-shaped glasses, which are the roof lights at dome structure, had the lowest sound absorption characteristics with α values of 0.01 and 0.03 at mid-frequency, respectively. These surfaces, being one tenth of the total interior surface area, should have contributed to the well-distribution of sound.

5.2 ORIGINAL Acoustical Features of Historical Turkish Baths

The ORIGINAL acoustical features of caldarium and tepidarium spaces for the Şengül Hamamı and Kadı Hamamı were discussed in terms of simulated global reverberation time (GRT). The acoustical ambient at the specified receiver location, which was located in iwan 6m away from the elevated platform in caldarium was defined by means of point RT, EDT, LF80, C80 and STI values. All data obtained were evaluated according to the optimum values, given in the literature (Barron, 1998; Benade, 1976; Egan, 1988; Long, 2006) for a satisfactory speech and musical performances.

The GRT at mid-frequency for the Kadı Hamamı was 2.6s while it was 1.5s and 1.4s for the women's and men's sections of Şengül Hamamı, respectively. The GRT values of these structures fell into the optimum ranges suggested for musical performances in unoccupied concert halls (Barron, 1998). The GRT at Kadı Hamamı was longer due to its larger volume, being three times larger than the women's section and four times larger than men's section of Şengül Hamamı (Tables 4.2 and 4.5, Figures 4.2, 4.3 and 4.8). Kadı Hamamı, with its long GRT value, was almost at the upper ranges of the optimum values while the GRT of Şengül Hamamı was at the middle ranges of the optimum values. A slight decrease at the GRT values should be expected for the occupied situations of these structures. Considering all, on the basis of simulated GRT values of these structures at mid-frequencies, the GRT value of Kadı Hamamı corresponded to the optimum ranges of musical performances, especially for symphonic music while the GRT values of Şengül Hamamı corresponded to the optimum ranges of musical performances, especially for opera activity, and of speech performance.

The point RT values at the specified receiver location were 1.7s for women's section of Şengül Hamamı, 1.3s for men's section of Şengül Hamamı and 2.6s for Kadı Hamamı. The point RT values were found to be similar with the GRT values of the structures, falling into the acceptable ranges for the musical performance. Similar difference can also be seen in point EDT values of both structures (Table 4.3 and 4.4).

Since EDT is a representative of RT, the sound decay occurs uniformly in the ORIGINAL case of both buildings, indicating that the Turkish baths were sound diffusing space and the reverberation is perceived uniformly by the users. In fact, The EDT values were calculated to be almost the same as the RT values, this showed that a proper sound diffusion was achieved inside the structures, at the specified receiver location (Figure 4.5, 4.12 and 4.19).

For the point LF80 values, as followed by the corresponding distribution graphs, the listeners close to the sidewalls where sitting area, received more lateral sound energy as compared to the listeners sitting on the central axis (Figures 4.21 -4.23). The average values of LF80 in 500 Hz and 1000 Hz bands fell in to the upper limits of acceptable ranges being 0.233 and 0.230 for women's and men's sections of Şengül Hamamı and 0.350 for Kadı Hamamı, respectively (See chapter 2) (Table 4.3, Table 4.6) (Baron, 2000; Marshall 2001). The reason for high value of LF80 comparable to symphonic halls is the presence of hard surfaces such as marble floors, sitting areas and walls. Since, the LF80 is related with the subjective parameter of envelopment, in the light of these results it can be told that the Turkish baths preserve "intimacy" and the feeling of "envelopment".

Acoustical properties of building should be compromised between speech and music. For good speech intelligibility, room volumes should be low thus RT became low for good music. For electronically unamplified musical activities, RT should be reasonably longer and C80 index should be in acceptable ranges between -4dB and 4dB (Long, 2006). Clarity and reverberance can be less reconciled. In extreme cases the two aspects are inversely related. In other words, if the long reverberation time exists, C80 is at low values (negative) and reverberance is high and vice versa. The point C80 values averaged in mid-frequency of 500 Hz and 1000 Hz seemed to fall into the acceptable range of -4dB to +4dB, providing preferable musical clarity (See chapter 2) (Table 4.3, Table 4.6, Figure 4.24) (Kuttruff, 2000). It was also detected that rear parts of baths (Tepidarium and halvets which are the small cells for washing separately) have high negative C80 values (Figure 4.25 to 4.27). This might be because C80 decreases with increasing distance.

In addition, unoccupied conditions of buildings have the lowest point C80 values, which show C80's dependency of RT (Barron, 1998; Long, 2006). The Kadı Hamamı and Şengül Hamamı seemed to be suitable for musical activities due to their proper GRT values at mid-frequency. Since all calculations have been done for the unoccupied conditions of the structures, the RT values should be expected to decrease while C80 values to increase for the occupied conditions of the structures.

It was well known that the acoustical features providing good speech performances, generally, were not appropriate for musical activities (Barron, 1998; Cowan, 2000; Long, 2006). The point STI values of Şengül Hamamı and Kadı Hamamı were found to range from 0.41 to 0.63 (Table 4.3 and 4.6). At the specified receiver location, among the historical bath structures examined, men's section of Şengül Hamamı had the shortest point RT of 1.3s and the highest point STI value of 0.63, falling into the ranges for fair speech intelligibility (Figure 4.15). The point STI value of 0.41 for the Kadı Hamamı fell into the range for poor speech intelligibility, signaling the difficulty in understanding of speech at the specified receiver location. The STI distribution graphs (Figure 4.29 to 4.31) showed that STI values were in the range of 0.7 and 1.0 at the front places, being close to the sound source. These values exhibited very good speech intelligibility, corresponding to the “excellent” due to high signal-to-noise ratio and high contribution of direct sound. In very few points, the STI values were in the range of 0.45 and 0.60 at the center of mid place, being between the sound source and receiver locations, exhibiting fair speech intelligibility. Both sides of the mid place had STI values in the range of 0.60-0.75, corresponding to good speech intelligibility, and those areas had better speech articulation than the center of mid place. At halvets, the STI values dropped to the ranges of poor speech intelligibility showing that the sound source on the elevated marble platform could not be perceived well from the halvets.

According to these results, Sengul Hamam and Kadı Hamamı were originally found to have quite well-designed acoustical features in terms of basic acoustical parameters. A conscious use of historical plasters having high sound absorption properties also signalled the experience of materials technology achieved in the past. Acoustical features depending on the frequencies may indicate the conscious acoustic design according to the social activities expected from the historical bath structures. The relationship between the social activities in the Turkish baths and their acoustical features should be investigated by further studies.

5.3 Marble-Cladding of the Lower Parts of Walls as a Trend in Repairs and Its Effect on the Original Acoustical Features.

According to recent research, there was a trend in repairs in the manners that lower parts of walls were covered with marble slabs and upper walls were remained with its original lime plaster, possibly to protect walls against water effect. This case was called as a REPAIR case in the study. The computer simulations show that those modifications introduced by Ottoman Turkish baths had a large influence on the acoustics of inside.

The acoustical features of the REPAIR cases for the caldarium and tepidarium spaces of Şengül Hamamı and Kadı Hamamı were discussed in terms of simulated global reverberation time (GRT). The GRT values obtained for the REPAIR cases of the structures were given in the Figures 4.6, 4.7 and 4.10. The GRT at mid-frequency for the Kadı Hamamı was 2.8s while it was 3.3s and 2.7s for the women's and men's sections of Şengül Hamamı, respectively. The GRT values of REPAIR cases for both structures were determined to be longer than those of ORIGINAL case (Figures 4.2-4.5 and 4.8-4.10) These long GRT values were above the upper limits of optimum ranges suggested for musical performance in unoccupied concert halls (Barron, 1998). It was understood that the marble clad walls at a certain height of 1.50m damaged the acoustical features of the ORIGINAL cases. The GRT results showed that the REPAIR case had poor speech intelligibility showing the difficulty in understanding of speech and muddy environment with distracting echoes.

The average RT values of the women's section were determined to be 3.2 s in mid frequency while it was 2.6 s in men's section and 3s in Kadı Hamamı at the specified receiver location (Table 4.5 and 4.8; Figure 4.6, 4.7 and 4.10). The point EDT values were almost same as the point RT values. The agreement between EDT and RT is an indication of diffuseness or directness of design. (Tables 4.5 and 4.8). The investigation carried out in this study was showed that from the graphs, RT values of the rear parts of the buildings (in halvet region) were higher values, mainly because of increasing distance from the sound source, decreasing the sound quality. In fact this is common feature any designed space that rear parts of the structures are generally lacking with acoustical quality.

The average values of LF80 in mid-frequency obtained for the specified receiver location were found to be 0.270 to 0.310 for the women's and men's sections of Şengül Hamamı, respectively, and 0.266 for Kadı Hamamı (Tables 4.5 and 4.8). These values, within the optimum ranges of 0.1 and 0.3, exhibited a strong impression of being surrounded or enveloped by sound due to the lateral reflections coming from the marble-clad reflective side walls.

The point average C80 values in mid-frequency were found to be -3.3 dB, -1.8 dB for the women's and men's sections of Şengül Hamamı, respectively and -2.2 dB and Kadı Hamamı respectively, at the specified receiver location (Tables 4.5 and 4.8). The point C80 values between 0 dB and -4 dB were within the acceptable ranges for the unamplified musical activities. According to the intelligibility rating given in the standards, at the specified receiver location of both structures it was determined to have poor speech intelligibility with the point STI values of 0.38 and 0.40 for the women's and men's sections of Şengül Hamamı, respectively, and 0.45 for Kadı Hamamı. These values clearly showed the difficulty in understanding of speech at the specified receiver locations.

According to the results obtained for the REPAIR case, in spite of LF80 and C80 values being in acceptable ranges, long RT and EDT values were above the upper limits of optimum ranges suggested for musical performance in unoccupied concert halls and low STI value caused with background noise and distracting echoes and naturally, less speech articulation and achieved in structures and also this event brought with increasing in vocal effort of the speaker.

5.4 The Effect of Improper Recent Repairs to the Original Acoustical Features

The AS-IS acoustical features of caldarium and tepidarium spaces for the Şengül Hamamı and Kadı Hamamı were discussed in terms of simulated global reverberation time (GRT). The GRT values obtained for the AS-IS cases of the structures were given in the Figures 4.5, 4.6 and 4.9. The GRT at mid-frequency for the Kadı Hamamı was 8.1s while it was 6.6s and 5.7s for the women's and men's sections of Şengül Hamamı, respectively. The GRT at Kadı Hamamı was longer due to its larger volume than those of Şengül Hamamı. The GRT values of AS-IS cases for both structures were considerably longer than those of ORIGINAL case (Figures 4.2-4.5 and 4.8-4.9) These very long GRT values revealed the poorly suited acoustical environment for musical performance and the severe loss of speech articulation suffering from the excess reverberation time.

Both buildings presented similar curves of RT value as a function of frequency (Figure 4.11) for the AS-IS case. The higher RT values were observed at lower frequencies, while the lower RT values were observed at the higher frequencies.
The point RT values at the specified receiver location were 6.8s for women's section of Şengül Hamamı, 5.6s for men's section of Şengül Hamamı and 8.3s for Kadı Hamamı (Table 4.4 and 4.7). The EDT values of Kadı Hamamı (Table 4.7) were also observed to be longer than the RT values. The point RT and EDT values were found to be considerably longer than those of ORIGINAL case, showing the high degree of sound diffusion and severe loss of articulation at the specified receiver location on quantitative basis.

The results obtained from the analyses of AS-IS case were summarized in Tables 4.5 and 4.7. Both buildings presented similar curves of RT value as a function of frequency (Figure 4.11) for the AS-IS case. The higher RT values were observed at lower frequencies, while the lower RT values were observed at the higher frequencies. This should be due to low sound absorption of coefficient of Oil painted cement based plaster. In other words, for the condition of the AS-IS case, the materials have the low α values at low frequency and α values increase with increasing frequency due to absorption of air at higher frequency. RT and EDT values were observed to be considerably longer than those of ORIGINAL case (Figures 4.11 to 4.18). Namely, longer RT and EDT values exhibited the high degree of sound diffusion and severe loss of articulation in spaces. Furthermore, the EDT of Kadı Hamamı (Table 4.7) was also found to be longer than the RT values, showing that a proper sound diffusion did not exist in the structure.

LF80 values of AS-IS case were almost the same as the LF80 values of ORIGINAL case, since marble tiles were used at side walls for both cases (Figures 4.19 to 4.22). Those values designated that sense of being surrounded by sound were good for AS-IS and ORIGINAL cases. Interpretations of the results showed that stronger lateral sound ray perceived by the human ears for two cases and even for REPAIR case were in satisfying range.

The C80 values of the AS-IS case were found to be lower than those of the ORIGINAL case, being less than -4 dB, at the specified receiver location, (Figures 4.23 to 4.26). These low C80 values designated the severe loss sound articulation. All results showed that the clarity of AS-IS case was of low range. These low values indicate poor definition, referred to subjectively as “muddy” sound, perceived by the users. In buildings it can clearly be observed that it had not uniform distribution of C80 values and not satisfying clearness of the sound in space. The C80 seems not to be good in AS-IS cases for that reason making these places not proper for musical performances.

According to the intelligibility rating given in the standards, for the AS-IS case of both Şengül Hamamı women’s and men’s sections and also Kadı Hamamı were found to have poor speech intelligibility (STI values: 0.30, 0.35 and 0.25) respectively, showing the difficulty in understanding of speech (Tables 4.4 and

4.7). These low STI values were due to longer RT values and also with background water flow noise to make the intelligibility worse (Figures 4.27 to 4.30). These buildings are not a suitable place for speech.

The echoes and the uneven distribution of the sound are the major acoustic problems of these Turkish baths. These are caused by the rigid surfaces with very reflective characteristics. In short, contemporary cement-based plasters were not suitable materials for the repairs of historical Turkish baths due to their incompatible acoustical properties, arising from their less porosity and less sound absorption coefficient characteristics. Thus, the analyses of 3D acoustical simulation proved that the well-designed original acoustical features of Şengül and Kadı Hamamı have been destroyed by recent repairs using such contemporary cement-based plasters.

5.5 Concluding Remarks

The study exhibited that the historical Turkish baths had originally well-designed acoustical features providing acceptable acoustical conditions for unamplified music performance as well as speech activities inside. This success was particularly due to the conscious use of historical materials, having high sound absorption characteristics. The knowledge on sound absorptive characteristics of historical plasters also revealed the experience of materials technology achieved in the past and established a successful acoustical ambient for historical bath structures.

The well-designed original acoustical features of these baths have been destroyed by the wrong repairs using cement-based plasters. These plasters were not suitable materials for the repairs of structures due to their incompatible acoustical properties, arising from less porosity and less sound absorption characteristics.

On the basis of simulated global reverberation time values, the AS-IS case, representing the present acoustical situation of historical Turkish baths after the wrong repairs using cement-based plasters, was determined to be poorly suited for musical performance and the delivering of speech messages to suffer from the excess of reverberation time. This meant that, due to the improper repairs, Şengül Hamamı and Kadı Hamamı exhibited muddy environment with background noise and distracting echoes causing severe loss of speech articulation and increase in vocal effort of speaker.

The marble-clad wall to a certain height, as the common-trend of recent repairs, was determined to destroy the well-designed original acoustical features of historical Turkish baths as well. The acoustical features of the REPAIR case were defined to have poor speech intelligibility showing the difficulty in understanding of speech and muddy environment with distracting echoes. Although a lime-based repair plaster compatible with the historical one was assumed to have used for the repairs, the use of marble at the lower parts of walls up to a 1.50m or 2.00m height should be expected to damage the proper musical and speech performances of historical Turkish baths considerably.

This study helped us to define the acoustical specifications for historical Turkish baths, which should be fulfilled by restorations. The in-situ acoustical recordings are necessary to compare the results obtained by the acoustical simulation method used in this study and to confirm its accuracy. Comprehensive studies are also needed to examine the acousto-physical properties of historical building materials, such as historic brick, brick mortar, exterior and interior plasters, the relation between their sound absorption coefficients and the moisture content. This knowledge is essential to define the acoustical requirements expected from the repair materials and their compatibility with the historic ones. The effect of geometrical forms, such as domes, vaults, arches and transition elements, to the acoustical ambient of the historical baths, should be investigated in terms of material use, dimensions of geometrical forms, height and volume of spaces.

The ODEON software, was a commonly-used computer-based acoustical simulation method for the acoustical assessment of contemporary structures. In this study, this method was adapted to the characteristics of historical Turkish baths. It was believed that this study was a good example, which can be applied for the acoustical assessment of similar historical structures on quantitative basis in order to make suggestions for their future repair works and maintenance. This knowledge is also useful to compare the original performance of the monuments with their present conditions and to discuss the incompatible interventions in terms of acoustical parameters.

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APPENDIX A

GLOSSARY OF ACOUSTICAL TERMS

ABSORPTION

The property of a material that changes acoustic energy into (usually) heat energy. A material or surface that absorbs sound waves does not reflect them. Absorption of a given material is frequency dependant as well as being affected by the size, shape, location, and mounting method used.

ABSORPTION COEFFICIENT

The fraction of sound energy that is absorbed at any surface. It has a value between 0 and 1 and varies with the frequency and angle of incidence of the sound.

ACOUSTIC

Acoustic is used to modify terms that designate an object, or physical characteristics, associated with sound waves; acoustical is used when the term being qualified does not designate explicitly something that has such properties, dimensions, or physical characteristics.

ACOUSTIC MATERIAL

Any material considered in terms of its acoustical properties. Commonly and especially, a material designed to absorb sound.

ACOUSTIC VELOCITY

(symbol [illegible]) speed of sound.

ACOUSTIC VIBRATION

With respect to operational environments, vibrations transmitted through a gas. These vibrations may be subsonic, sonic, and ultrasonic.

ACOUSTICS

The study of sound, including its production, transmission, and effects. Those qualities of an enclosure that together determine its character with respect to distinct hearing.

ARTICULATION

A quantitative measure of the intelligibility of speech; the percentage of speech items correctly perceived and recorded.

AUDIBLE FREQUENCY RANGE

The range of sound frequencies normally heard by the human ear. The audible range spans from 20Hz to 20,000Hz.

BACKGROUND NOISE

Total of all sources of interference in a system used for the production, detection, measurement, or recording of a signal, independent of the presence of the signal.
Noise from all sources unrelated to a particular sound that is the object of interest. Background noise may include airborne, structure borne, and instrument noise.

BAND

A defined portion of either the audio or radio frequency spectrums. A specific part of the frequency spectrum such as AM, FM, VHF, UHF, etc.

BANDWIDTH

The frequency range passed by a given device or structure.
The total frequency range of any system. Usually specified as something like: 20-20,000Hz plus or minus 3 db.

DECIBEL

The human ear responds logarithmically and it is convenient to deal in logarithmic units in audio systems. The bel is the logarithm of the ratio of two powers, and the decibel is one tenth of a bel. Symbol, dB.

DIFFRACTION

The distortion of a wave front caused by the presence of an obstacle in the sound field.

DIFFUSE SOUND FIELD

Sound field in which the time average of the mean-square sound pressure is everywhere the same and the flow of acoustic energy in all directions is equally probable.

DIFFUSION

The random scattering of sound waves. A convex surface acts as a diffuser.

DIFFUSOR

A proprietary device for the diffusion of sound through reflection-phase-grating means.

ECHO

A sound reflected off a surface that arrives at the listener after the direct sound. Sometimes thought of as reverberation, but an echo is very distinct while reverberation is a mixed together sound which decays gradually.

FLUTTER ECHO

An acoustic echo in a room between two parallel flat surfaces. A reverberation that doesn't gradually decrease, but has multiple distinct echoes which causes degradation in speech intelligibility.

FREQUENCY

The number of times something is repeated. In acoustics, it refers to the number of complete sound waves that pass a given point in a given time. Usually measured in Hertz (one cycle per second). Typically refers to the pitch of a sound, how high or low it is. The higher the number, the higher the pitch.

HARMONIC

A frequency that resonates in response to a fundamental (primary) frequency. Sometimes, when a certain frequency is generated (a fundamental), it will also cause another frequency or frequencies to start as well. These are called harmonics.

IMPEDANCE

The opposition to the flow of electric or acoustic energy measured in ohms.

IMPULSE

A very short, transient, electric or acoustical signal.

IMPULSE RESPONSE

Sound pressure versus time measurement showing how a device or room responds to an impulse.

INVERSE-SQUARE LAW

The name given to a physics law which states "for each doubling of distance a sound wave travels along a path, the level of sound will drop to 1/4th (the inverse of the square of the distance)". Doubling the distance reduces the sound pressure level (SPL) by 6db.

LOUDNESS

A subjective term for the sensation of the magnitude of sound. The subjective response to a sound level.

OCTAVE

The interval between two frequencies having a ratio of 2:1.

The range of frequencies between a given point and twice the frequency of the given point. Middle A on a piano has a frequency of 440Hz. One octave higher (the next A) the frequency is 880Hz, twice the original frequency.

OCTAVE BAND

Groups of frequencies defined by standards where the upper frequency of each band is equal to twice the lower frequency of the next higher band. Octave bands are usually named by their geometric center frequency. For example, the octave band extending between 44.7 Hz and 89.1 Hz is called the 63 Hz octave band. The octave band extending between 89.1 Hz and 178 Hz is called the 125 Hz octave band. The full complement of octave bands in the audible frequency range is as follows: 31.5, 63, 125, 250, 500, 1,000, 2,000, 4,000, 8,000 and 16,000 Hz.

ONE-THIRD OCTAVE BANDS

Frequency ranges where each octave is divided into one-third octaves with the upper frequency limit being 2* (1.26) times the lower frequency. Identified by the geometric mean frequency of each band.

RASTI

Rapid Speech Transmission Index. A scale which shows the intelligibility of a room or sound system based on the measured consistency in modulated frequencies within the human vocal range between the source and the listener.

REFLECTION

A sound wave that has been "bounced off" a surface--not direct sound from the source. Sound that goes from a source to a surface and then is reflected back to the listener. This will then combine with the direct sound (and other reflected sound waves) and cause phase cancellations. (which results in bad sound).

REVERBERATION

The sound that's reflecting off surfaces in a room after the source has stopped producing that sound wave. Reverberation is usually considered to be a smooth decay in level of sound until it's not perceptible.

REVERBERATION TIME

The time required for the sound in an enclosure to decay 60 db, the time required for the time average of the sound energy density, initially in a steady state, to decrease, after the source is stopped, to one-millionth of its initial value. The unit is the second.

SIGNAL-TO-NOISE RATIO

The ratio between the nominal level of a signal and the general circuit noise level (noise floor) measured in db. All electronic devices produce noise. The S/N ratio is a measure of how quiet the device is by indicating how low the level is of the inherent noise.

SOUND ABSORPTION

At a specified frequency or in a specified frequency band, property of a material or an object whereby sound energy is converted into heat by propagation in a medium or when sound strikes the boundary between two media.

SOUND ABSORPTION COEFFICIENT

The practical unit between 0 and 1 expressing the absorbing efficiency of a material. It is determined experimentally.

SOUND INTENSITY

Average rate of sound energy transmitted in a specified direction at a point through a unit area normal to this direction at the point considered. Unit, watt per square meter (W/m{sup 2}); symbol, I.

SOUND LEVEL

Specifically, a weighted sound pressure level, obtained by the use of metering characteristics and the weightings A, B, or C specified in American Standard Publication Z24.3-1944: Sound Level Meters for Measurement of Noise and Other Sounds. The weighting employed pressure is 0.0002 microbar. A suitable method of stating the weighting is, for example, The A-sound level was 43 decibels.

SOUND LEVEL METER

Device used to measure sound pressure level with a standardized frequency weighting and indicated exponential time weighting for measurements of sound pressure level, or without time weighting for measurement of time- average sound pressure level or sound exposure level.

SOUND POWER

Sound energy radiated by a source per unit of time. Unit, watt (W); symbol, W.

SOUND POWER LEVEL

Logarithm of the ratio of a given sound power in a stated frequency band or with a stated frequency weighting, to the reference power of one picowatt (1 pw). Unit, bel (B); symbol, LW.

SOUND PRESSURE

The sound pressure is the total instantaneous pressure at a point in space, in the presence of a sound wave, minus the static pressure at that point.

SOUND PRESSURE LEVEL

(Abbreviated SPL): Ten times the base-10 logarithm of the time-mean-square sound pressure, in a stated frequency band (often frequency-weighted), divided by the squared reference sound pressure of 20 Pa, the threshold of human hearing.

SPEECH INTELLIGIBILITY

How well you can understand what is being said. Though you may "hear" the sound, you may not understand it (and it's useless). Measurements can be taken to quantify what the intelligibility of a room and/or sound system is.

SPEECH TRANSMISSION INDEX, STI

A single number that indicates the effect of a transmission system on speech intelligibility.

WARMTH

A listening term. The opposite of cool or cold. In terms of frequency, generally considered the range from approx. 150Hz-400Hz. A system with the "proper" warmth will sound natural within this range.

WAVELENGTH

The distance a sound wave travels in the time it takes to complete one cycle.

*Source: http://www.webref.org/acoustics/acoustics.h*tm