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ACOUSTIC SOLUTIONS IN CLASSIC OTTOMAN ARCHITECTURE

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ACOUSTIC SOLUTIONS IN CLASSIC OTTOMAN ARCHITECTURE

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Introduction

Throughout history, Anatolia became the birthplace and cradle of many great civilizations. Due to a number of factors, the Turks held a significant part in these series of civilizations, beginning with the oldest that our historical knowledge has been able to determine – the Hatties (Khatties). The first reason for this is that the preceding civilizations were not demolished by the Turks; on the contrary, they protected them and also carried them forward. Another reason is the monumental buildings they built and the technology they applied to these buildings. Whenever Anatolian Turkish works and their related technology are spoken of, the first name that comes to mind is that of the Turkish *Architect Sinan*. The construction technology used by Sinan has become legendary.

Sinan's renowned success in the acoustic design of mosques has previously been studied in detail.[1] The acoustic systems he applied, especially Helmholtz (cavity) resonators technology, are among the most successful applications of acoustic science. But it must be made clear here that cavity resonator technology was not new in Anatolia. The Roman architect-engineer Marcus Vitruvious Pollio, who lived in the first century CE, gives information on the construction technology of his age in his work titled *Ten Books on Architecture (De architectura libri decem).*[2] In the fifth book, the writer takes up the subject of public buildings and gives information concerning their architecture and construction. In the third, sixth, seventh and eighth chapters of this book, acoustic data related to the construction of theatres are explained in detail. The fifth chapter, Sounding Vessels in the Theatre, is completely devoted to cavity resonators. In this chapter he explains that sounding vessels (cavity resonators) made of bronze must be placed in the theatre structure to reinforce the quality and harmonic structure of sound and he explains their resonances, installation location and form in detail. In the last section of the chapter in which theatres' sounding vessels can be found is discussed and he gives the theatres in the Greek city states as an example. In addition, he relates that a man named *Lucius Mummius,* after destroying the theatre in Corinth, took the bronze vessels from there to Rome and sold them. He then made an offering to the Temple of Luna with the money he made from the selling. Later, the chapter relates how a number of experienced architects who built small theatres were forced by economic reasons to use earthenware vessels (in the place of bronze ones) that gave the same resonance and obtained positive results.

The vessel described in this document, which gives important data for Anatolian civilizations, is actually one of the first examples of the cavity resonator applications. However, this technology did not end with Ancient

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1 The writer has researched the acoustic data of Sinan's mosques and the results of the Research have been published. See: Mimar Sinan Camilerinin Akustik Verilerin Degerlendirilmiesi, Mimar-basi Koca Sinan-Yasadigi Cag ve Eserleri, T.C. Basbakanlik Vakiflar Genel Mudurlugu publications, (Istanbul 1988).
2 Vitruvius. The Ten Books on Architecture. Translated by M. H. Morgan, Dover edition, Dover publication, (New York, 1960)

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Greece or the Roman Empire; on the contrary, their existence continued and developed. Moreover, new examples based on acoustic knowledge were applied.[3] These examples are frequently seen in both Seljuk and Ottoman works. The *Gevher Nesibe Sultan Darusshifa* (A. C. 1205) in *Kayseri* from the Seljuk period is one of the best examples of this. In this hospital the music played for therapeutic purposes was heard in the patients' rooms by means of sound channels. These is one of the clearest examples of the continuing development of the applications of acoustic knowledge in Anatolia. The widespread use of cavity resonators is often seen in both Seljuk and Ottoman works.

We see that the development of applications and technology covering acoustic knowledge reached its peak with Sinan. The results obtained from the mosques selected for our acoustic research on Sinan's mosques support this view. In the investigation of three large mosques, it is seen that attention was paid to the relation between the sound power capacity of source and the size (volume) and that the goal of obtaining sufficient sound level affected the layout of plans. For this reason, before specifically taking up Sinan's technology, which reached the top level of today's definition on acoustic design and applications, we believe it is useful to investigate the purpose of acoustic science and the applications based on acoustic knowledge.

ACOUSTIC SCIENCE

The exact meaning of the word acoustic is “Of or relating to the science of sound”. Early works dealing with sound and hearing are seen long before Vitruvius. The numerical observations made by Pythagoras (580-500 BC) are accepted as the first works. Later, we encounter Aristotle's (384-322 BC) work titled *Sound and Hearing.* Others followed this. In these works, the basic aims are to physically define sound and to determine the necessary conditions for better hearing. In this period there was no concept of noise, as we understand it today. The existent noise was natural sounds such as thunder and storms and the sound of weapons during wartime. Noise (man-made noise) appeared with the Industrial Revolution. Humanity became aware of noise and took measures against it only after the Second World War. In this way noise control became a branch of acoustic science.

Today's architectural acoustics is formed of two branches:
1. Noise control
2. Room acoustic.

3 The “Acoustic knowledge” term is used instead of “acoustics science”since acoustics was not a science in those years. Hence works for better intelligibility and better hearing had been applied based on the then knowledge of sound. But, after discussing Sinan’s technology, it will be seen that applied technology defines acoustics science. The reason of using the “acoustic system” term for cavity resonators is that, physical definition of such resonators have been done by acoustic science and they work as a system.

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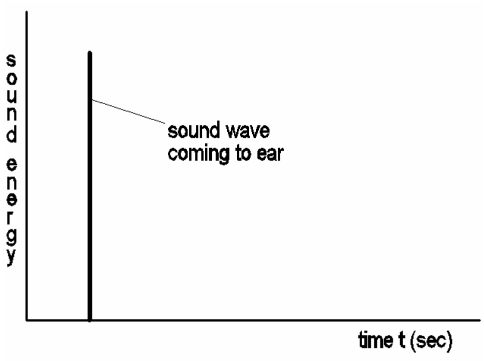

Figure 1. Instantaneous (no reflection) sound energy.

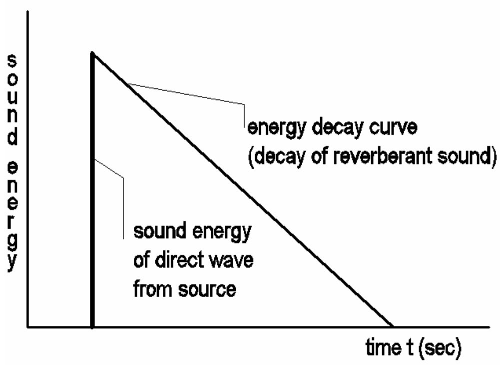

Figure 2. Energy decay of reverberant Sound

As there was no noise problem recognised in that period, the scope of acoustic works were limited to "room acoustics" and was aimed at getting better hearing conditions. In order to achieve this aim, it is necessary to realize these two basic conditions:

1. Realizing a homogenous dissipation of sound energy in a room (diffuse field).
2. Realizing the decay of sound energy (reverberation time) at the optimum level.

The first condition, as will be easily understood, that in a room whose basic function is related to sound, the homogeneous distribution of the sound energy in the room must be realized. Sinan's making use of components on the boundaries of a room for this purpose and his realizing distribution of sound in all directions by the activity formed on these surfaces has been described in detail in the writer's previous publications.[4] It is necessary to make it clear here that, in spite of all the positive applications, the dome that covers a mosque is one of the most inconvenient forms in acoustics. This subject and the applied solutions will be discussed later.

4 See footnote 1.

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We can define the second condition as follows; sound energy is emitted from its source in spherical waves. If, even in the outdoors, the waves do not strike and are not reflected by any surface or component, they will continue their travelling until all the sound energy will be absorbed by air. A listener in the path of the sound wave's emission perceives the coming and passing energy wave during the instant that it contacts his ear (Figure 1.). Regarding the speed of sound, it is understood that this time is extremely short. In enclosed spaces, the sound energy reflected from the boundaries continues its existence while decreasing (Figure 2.). We call this physical event “reverberation”. The time of reverberation is lengthened or shortened in relation to the sound absorption characteristics of components found in the room and the surfaces at the boundary of the room. The decay time of sound energy is called “reverberation time”.[5]

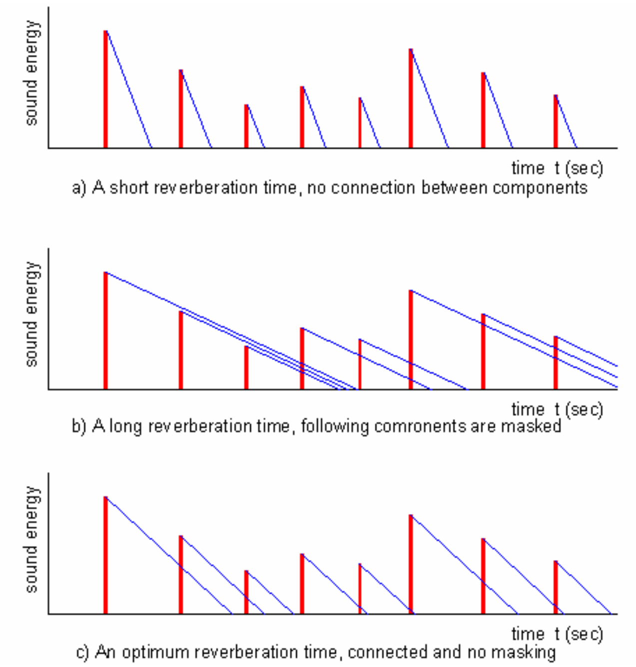

Figure 3. Effect of sound energy decay on Intelligibility due reverberation time

5 Reverberation time is defined as the time which elapses from the moment the sound source is switched off until the average energy density in the room has fallen by 60 dB of its steady value.

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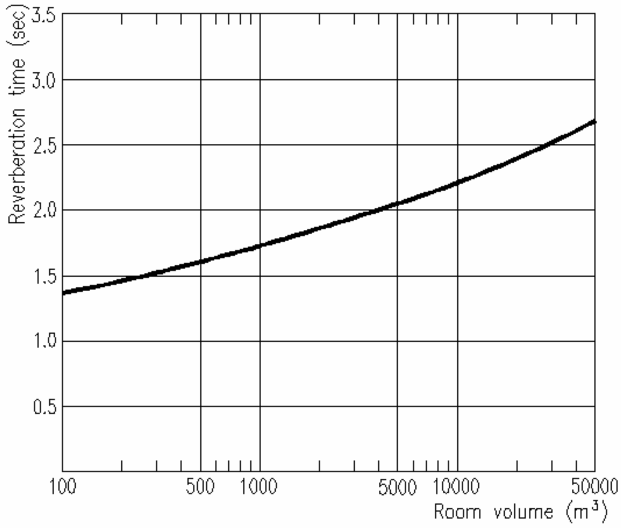

Figure 4. Recommended reverberation time for mosques

The sound field around us is formed from a series of sound energy components that always follow one another. These components, from both the point of view of energy intensity and frequency characteristics, usually differ from each other. This is the nature of sound for human voices, and sounds in nature and in music. The human ear always seeks reverberation and in order not to separate sound components from one another wants to connect each one to the following one with a reverberation (sound energy decay) curve. So, realizing optimum reverberation time gives better hearing conditions. A short reverberation time leads the ear to feel unsatisfied, and a long reverberation causes components to mask the following ones, which results in insufficient intelligibility or even unintelligible hearing (Figure 3). For this reason, the problem in a room is achieving an optimum reverberation time according to the function of sound like speech, music, drama, etc. The sound absorption characteristics of finishing materials of boundaries and all components in the room give this value. The recommended optimum reverberation time curve for mosques is given in Figure 4 as a function of the size of the room and the time. In this description of the reverberation time curve, suggested by the writer, the function of the sounds formed in the mosque was taken as a basic factor and attention was paid to the reflections achieving a divine aesthetic quality to the sound.[6] Therefore, the values determined are longer than the reverberation time necessary for normal conversation.

6 See: "Sinan Eserlerinde Akustik", Turk Vakif medeniyeti Cercevesinde "Mimar Sinan ve Donemi Sempozyumu," Vakiflar Genel Mudurlugu publications, (Istanbul 1989).

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Effect of Cavity Resonators and Domes in Architectural Acoustics

After defining the basic concepts related to acoustic design in rooms, we can investigate the functions of the components in a dome described as bronze vessels by Vitruvius, by the Ottomans as jar and cavity resonators (Helmholtz resonators) in acoustics.

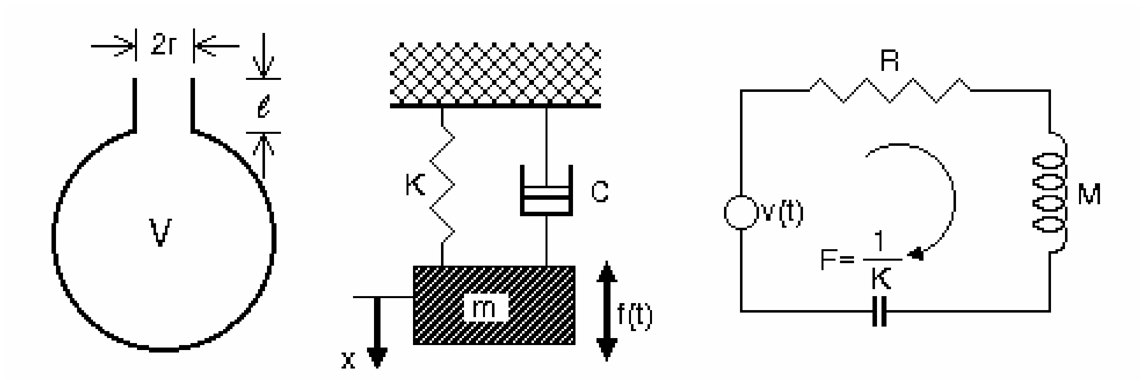

Figure 5. a) Cavity resonator, b) Simple mechanical oscillators, c) LCR electrical circuit

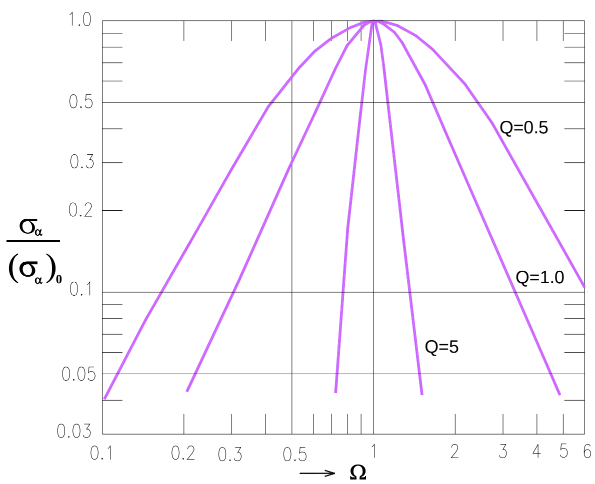

Figure 6. Equivalent absorption cross section areas ratio of cavity resonators

Cavity resonators, despite their small dimensions, are effective acoustic systems. Because of their small dimensions the medium (air) movement inside is analogous to those mechanical systems having lumped mechanical elements of mass, stiffness and

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resistance. Cavity resonators, therefore, can be discussed in terms of an analogous simple mechanical oscillators or LCR electrical circuits (Figure 5). Such a system consists of rigid enclosure, a neck that provides a connection to this cavity external medium.7 Without getting into physical equivalents, the air in the system's neck acts as a mass by oscillating with the effect of an incident sound wave. The air in the system's cavity acts as a spring in this oscillation, by compressing and expending, and thus provides the stiffness element. The total resistance of the air mass in the neck and radiation resistance forms acoustic resistance.

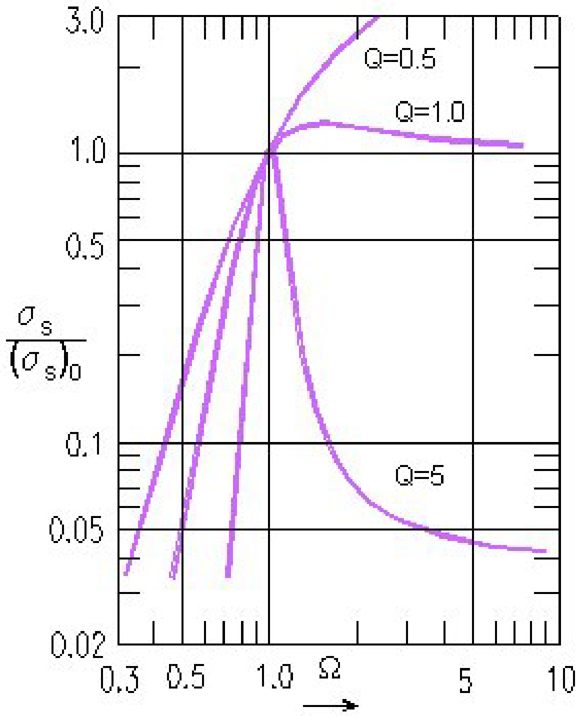

Figure 7. Equivalent scattering cross section areas ratio of cavity resonators

The system acts as an absorber in a narrow frequency band with a centre frequency in which resonance occurs. By decreasing the system's quality factor Q (by increasing interior resistance), it is possible to widen absorption frequency band to a certain degree. In this situation, a decrease in the absorption is seen. In Figure 6 the ratio of the equivalent absorption cross section area (σ_α) to the equivalent absorption cross section area at resonance frequency (σ_α)$_o$ is given as a function of the ratio of frequency to resonance frequency (Ω). One of the other characteristics of the system is, again in a specific frequency band, to reradiate incident sound energy homogeneous in all direction as if it were source itself. In Figure 7 the ratio of the equivalent scattering cross section area (σ_s) to the equivalent scattering cross section area at resonance frequency (σ_s)$_o$ is again given as a function of the ratio of frequency to resonance frequency (Ω). As will be seen in the figure, when the system's quality factor Q is reduced enough, the system is able to perform like a sound source system in the frequencies above the resonance frequency. Cavity resonators, particularly because of their effects at low frequencies, are used to prevent the resonance of standing waves inside a room and for the purpose of getting homogeneously distributed sound energy.

7 The writer has investigated Sinan's acoustic technology and the results published, in this publication the physical characteristics of cavity resonators are given in detail. See: "Sinan ve Bosluklu Rezonatorler", Gazi Universitesi Muh.-Mim. Fakultesi Dergisi, vol. 3, no. 1-2, (Ankara 988).

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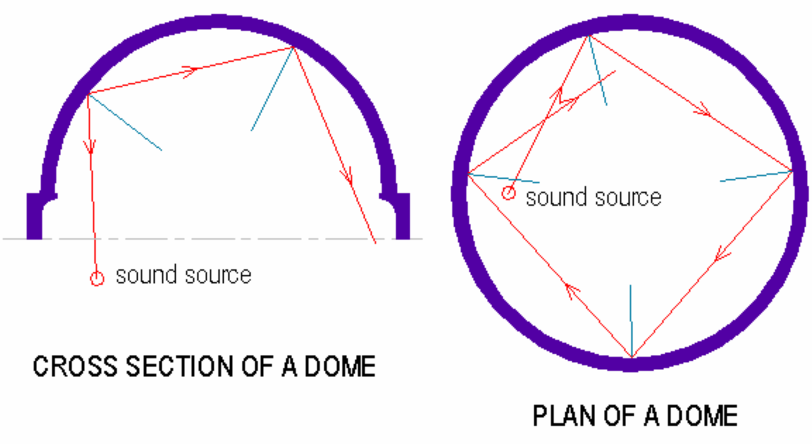

Figure 8. Behaviour of sound energy in a dome

Acoustic properties of the Dome

As explained above, the dome form is one of the most inconvenient forms in acoustics. The reason is due to the concave forms of the domes, the incident sound energy does not go out without reflecting several times in the dome. Because of this the reflected sound energy from the dome reaches back to the room with a time delay. So the result is echoes or noise in the room and reduction on the percentage of intelligibility. In Figure 8 the behaviour of sound energy in a dome is shown both in plan and cross section. As can be seen from the figure, the reflected sound energy that is increasingly delayed, especially in large domes, is a cause of echoes. The function of cavity resonators, whose characteristics were briefly given in the previous subsection, begins here. Cavity resonators, placed in a dome, prevent the reflection of sound energy and reradiate it throughout the room. By reradiating the incident energy in all directions, the room becomes a diffused sound field and the danger of echoes due to delayed reflections from dome is eliminated. Besides getting a diffused field, the sound coming from the dome shortly after the direct sound, creates a divine effect in the atmosphere of worship. It is believed that this application became a tradition in Ottoman

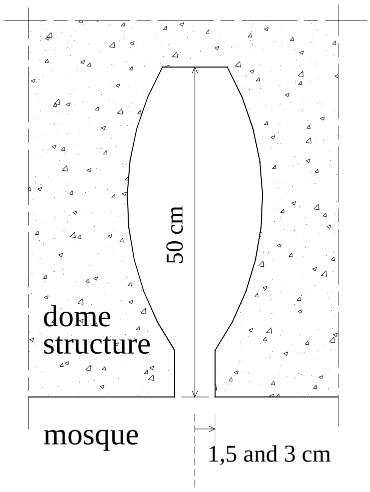

Figure 9. Cross section of the resonators found in the dome of the Sultan Ahmet Mosque

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mosques.

To investigate the state of resonators, has however not been possible in every mosque dome. Such an opportunity only comes about during restoration work and that opportunity was found in the Sultan Ahmet (Blue) Mosque (See Photo 1 and Figure 9). The continuation of restoration in 1986 gave us a chance of detailed inspection in the main dome and seventy-five resonators were found on three rings at the dome.[8] Unfortunately, all of these resonators had been plastered over later. Some of them had even plugged with various components (See Photo 2). The same problem held true for the Selimiye Mosque in Edirne. According to authorities in charge of the last restoration work, "they found a large number of earthenware jars (resonators) in the dome, but all of them had their openings covered with bricks which had been plastered over. After cleaning the interiors of the resonators the bricks were replaced and plastered over once more". Again, Dr. Beyhan Ercag, who was in charge of restoration, writes in her Ph.D. thesis that during the course of

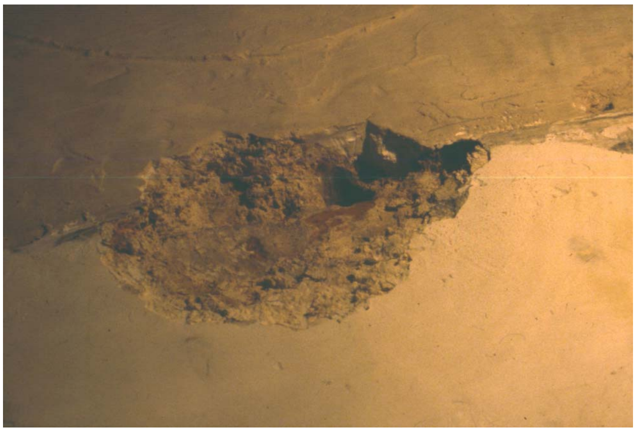

Photo 1. The opening of a resonator in the dome of the Sultan Ahmet Mosque

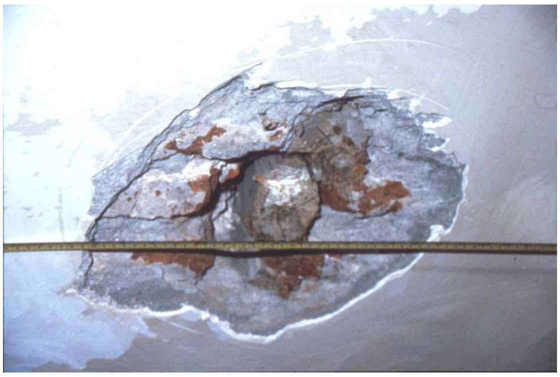

Photo 2. One of the plugged resonators in the dome of the Sultan Ahmed Mosque

8 See note 1.

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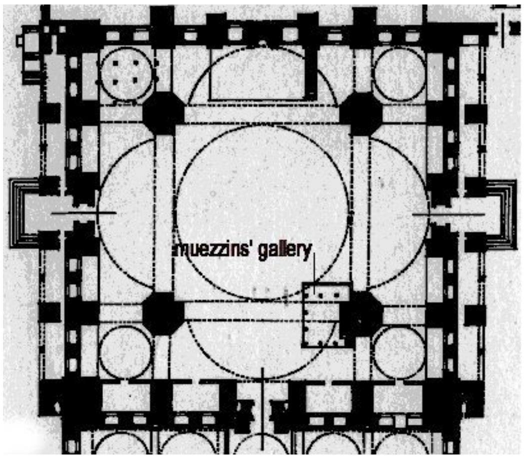

Figure 10. Plan of the Shehzade Mosque

restoration, 144 resonators were found in Shehzade Mehmet Mosque (See Figure 10).[9] On the other hand, during the observation made at Kadırga Sokullu Mehmet Pasha Mosque, traces of holes believed to be the openings of resonators were found. There were thirty-six holes in the main dome and 42 to 45 in each of the quarter domes. Naturally, when the openings of the resonators are completely closed they are unable to function. The result of these causes, particularly in large rooms' and at low frequencies, undesirable reverberation curves. As a matter of fact, this expectation was confirmed by measurements of the reverberation time made in the Suleymaniye and Selimiye Mosques (See Photo 3). In both mosques, a long reverberation time was measured, especially in the low frequencies. The irregular and prolonged reverberation times were also recorded for those frequencies

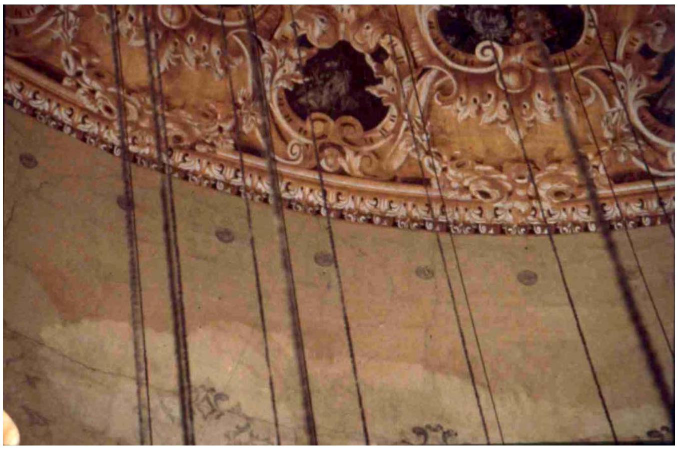

Photo 3. The opening of resonators in the dome of the Suleymaniye Mosque

9 Ercag, Beyhan, Istanbul'daki Bazi Mimar Sinan Camilerinde Ic Bezeme Programinin Gecirdigi Evreler, (Unpublished doctoral thesis), (Istanbul 1996).

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INFLUENCE OF ACOUSTIC DATA IN ARCHITECTURAL DESIGN

The results of our investigation to define acoustic properties of Sinan's mosques proved the abundance of his knowledge and applied technology on acoustics and his ability in utilising them in architectural design. Especially, the obtained data from mosques other than his two large ones supports this view.[10] Although the measured reverberation times of Suleymaniye and Selimiye were quite reasonable at middle and high frequencies, there were serious problems at low frequencies. The basic reason for such results is the mistakes that were made during the restoration activities without having sufficient knowledge of the applied technology. On the other hand, because of the size of Sinan's two big mosques, the delayed reflections have negative effect at those frequencies. On the other hand, the existence of *muezzin mahfil* (a gallery for the cal to prayer) in different locations in all three mosques is considered important; although a small *mahfil* was added on to two pillars at the back of the Suleymaniye, it was not desired in the Selimiye. The data led us to analyze the plan graphics of the three big mosques again; the analysis showed us improvement on Sinan’s acoustical concept during their design process and also his awareness of the intelligibility problem.[11] It has been determined that, with this awareness, Sinan began to search for a solution to get sufficient intelligibility and he combined architectural design with acoustic design. The data given below led us to these result.

Type of sound source	Maximum room volume (m^3)
Average speaker	3000
Experienced speaker	6000
Instrumental or vocal soloist	10000
Large symphony orchestra	20000
Massed choirs	50000

Table 1. Maximum room volume according to type of sound source within

First of all, the calculations of the interior volume of all three mosques show us that there is a lack of sound power due to sound sources in the mosques. The maximum volumes of the rooms are given in Table 1. The Shehzade Mehmet Mosque, in spite of being the smallest of the three mosques, has an interior volume of almost 50,000 m^3 (See Figure 10). Looking at Table 1, we can see that only massed choirs can produce the sufficient sound power for the room with that size of interior volume. The *muezzin's mahfil* in this mosque is located next to the northwest pillar. It is evident that although there are cavity resonators in the dome, the sound energy will remain insufficient and the total sound energy of those working at the *muezzin's mahfil* will not be the equivalent of large choirs.

10 Because restoration work was being done on the Sehzade Mehmet Mosque during the course of the research no research was conducted there. Acoustic data were taken from the Suleymaniye and Selimiye Mosques.
11 The writer has given the result of analyses of plan graphics in detailed in his paper “Use of Cavity Resonators in Anatolia Since Vitruvius. The Seventh International Congress on Sound and Vibration Proceedings. Publications of International Institute of Acoustics and Vibration, V. 3, pp. 1621 – 1628, Munich, Germany, 2000.

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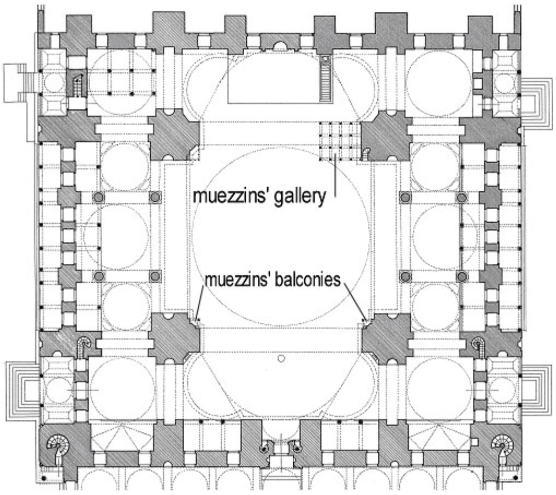

Figure 11. Plan of the Suleymaniye Mosque in Istanbul

It is realized that besides enlarging the interior volume of the Suleymaniye Mosque even more, Sinan tried to increase sound power by a number of sources. For this purpose, he placed the muezzin's mahfil near the *mihrab,* next to the southwest pillar and in addition, he added small *mahfils* (balconies) to the two north pillars (Photo 4.). The data show awareness of the need for extra sound power during the design process of this mosque with interior volume approximately 88,000 m^3 and the data also demonstrate the greatness of both the period's and Sinan's acoustic knowledge. It must be noted here, however, that there is also a lack of knowledge in this application. In such a large enclosed volume having more than one source located at different places and with the repetition of the sounds from the first and following sources naturally create duplicate sounds or even multiple sounds resulting in unintelligible sound or noise. In Figure 11 the plan of the Suleymaniye Mosque in Istanbul is given.

Photo 4. One of the small Mahfills in Suleymaniye Mosque

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Photo 5. The Acoustic Space and the *muezzin's mahfil* in the Selimiye Mosque

For the Selimiye Mosque in Edirne, it is evident that Sinan made an effort to achieve a reasonable solution to the acoustic problem.[12] (See Figure 12) For this purpose, he designed a total space for the interior of the mosque, not divided into spaces and reduced to the size of room. The interior volume of the Selimiye Mosque is approximately 75,000 m^3 and, naturally, it is evident that the problem of the power of the sound source will arise. To overcome this problem, Sinan placed the *muezzin's mahfil* exactly in the centre of the total space (see Photo 5). The dome and also cavity resonators are directly above the sound source. The resonator system that will diffuse the sound energy into the room, being close and having no effect of reflected sound, will take the sound energy directly from the source and diffuse it throughout the entire room. Here intelligence shows its creativity, and for the first time in the history of civilization, we encounter an acoustic space. The sound energy coming from above defines a space - an acoustic space. It must be remembered that for Sinan's design there is no application without a reason.

For many years, historians have sought the answer to the question "after creating a total space, why did he put the muezzin's mahfil right in the centre". Now we can easily say; "The answer is to create an acoustic space".

12 The writer has given the analyses of total space in detailed in his paper "Evolution of Acoustics and Effect of Worship Buildings on it. Proceedings of the Forum Acousticum Sevilla 2002 -16-20 September 2002. Revista de Acoustica, V. XXXIII, ISBN: 84-87985-06-8, Madrid, Spain, 2002.

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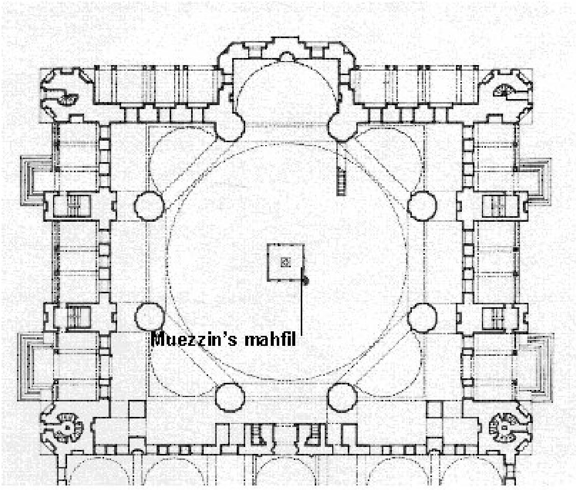

Figure 11. Plan of the Selimiye Mosque in Istanbul

CONCLUSION

In this work, we have briefly evaluated applied acoustic systems throughout history, especially in Ottoman period. The high level of development and applied technology that we have determined is surprising. Here it must be made clear that satisfactory researches have not been carried out in all relevant technical sciences, as we have seen in acoustics and many technical data have yet to be evaluated sufficiently. The air circulation in mosques and the soot-cell of the Suleymaniye Mosque are typical examples of not deeply investigated data. During the course of our research we saw a number of clay pipes going into the walls or opening into the *mihrab* in both mosques that are under the process of restoration and half ruined. These beg questions which must be answered. In addition, in the same mosques we saw a number of different types of plaster. It still is not completely clear whether or not these are a product of the technology which determined their characteristics due to their purpose. These topics, until now, have only interested art historians and architectural historians. These research projects now require the participation of engineers, physicists and other technical specialists. It should not be forgotten that with every restoration, a part of technological products that are not completely understood are completely lost or remain under plaster. It is necessary for this work to be carried out by a team composed of experts from many branches of science.

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