EVOLUTION OF ACOUSTICS AND EFFECT OF WORSHIP BUILDINGS ON IT

PACS REFERENCE: 43.55.GX

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ABSTRACT

Researches have shown that the cavity resonators have had wide range of use, both in Anatolia and Europe, since ages. Similar acoustic systems have also used in the Far East countries. These results lead us to discuss the importance of such systems for ancient societies. It is known that Greek drama developed from religious dances and ceremonies, and performed in ancient theatres. The acoustic systems used in those theatres were cavity resonators, which is the oldest acoustic systems known in architectural acoustics. In the medieval ages their use became more common in mosques and church buildings. Aim of this paper is to discuss the impact of religious rituals and ceremonies on. In this discussion, acoustic properties of worship buildings and evolution of acoustics will be the main issue.

INTRODUCTION

Marcus Vitruvius Pollio, Roman architect, who lived in the first century, was the author of the original engineering handbook. He described existing practices in design, construction, and other related engineering disciplines in his book titled as ***De architectura libri decem*** (**Ten books on architecture)** (1). He carefully described existing practices, not only in the design and construction of buildings, but also in areas those are today thought of as engineering disciplines. Such varied topics as the manufacture of building materials and dyes (material science), machines for heating water for public baths (chemical engineering), the design of roads and bridges (civil engineering), and also theatres and sound systems in amphitheatres (acoustics) are included in his treatises (2).

Although, some work had been done on sound and hearing before, Vitruvius is accepted as the first author who has mentioned acoustical systems for better sound quality. In his fifth book he tells the design rules for amphitheatres and emphasizes on **acoustics in amphitheatres**. Naturally without referring physical wave motion, his explanation of sound propagation analogising to the concentric waves propagating on the surface of water is very interesting. Chapter V, titled as **Sounding Vessels in the Theatre** begins with explanation of using bronze vessels to increase clearness of sound and in the last article he mentions that in none of theatres in Rome these vessels have been employed. Then he refers antique Greek amphitheatres as examples. Following four chapters are also subjected some details on theatre design.

ACOUSTIC SYSTEMS IN ANTIQUE THEATRES

It is obvious that the known original engineering handbook includes sections subjected amphitheatres, acoustics of amphitheatres and known oldest acoustical systems, which are cavity resonators. Although the temples of the ancient Egyptians may have provided the setting for their dramas, and the theatral area adjoining the palaces at Knossos and Phaistos, Crete (2000-1600 B.C.), may well have served as a place for ritual dances and ceremonies of a dramatic nature. It was in ancient Greece that the Western type of theatre began. Greek drama developed from religious dances performed by a chorus on a flat area levelled off on the slope of a hillside, the audience standing on the slope above; often the most suitable ready-made site was the circular threshing floor (3). These properties of amphitheatres were result of necessities of its function; Those were better hearing lines and better sight lines, and use of sounding vessels (cavity resonators) for better hearing even though there are some contradiction and confusion in Vitruvius writings on sounding vessels.

The vessels, those were mentioned by Vitruvius for Antique Greek theatre, may easily be named as the oldest cavity resonators used in architectural acoustics, and also the origin of cavity resonators used in Anatolia. If answer is yes, using such developed acoustical systems in those days, nearly 24 centuries ago is very impressive. But, Vitruvius' definition for sounding vessels does not define cavity resonators adequately. Serious contradiction and confusion were recognized in definition of them. After reading Isenour's criticism on De Architectura it is realised that, although technical subjects were given in detail by writing or drawing, form or dimensions of vessels were not given (2). Vitruvius also mentions that he cannot point to any example in the city of Rome. So, it is thought that Vitruvius had heard a lot about sounding vessels but had never used or seen any of them. It is also thought that probability of using a kind of cavity resonators under the name of "sounding vessels" by ancient Greeks is very high. It must be mentioned also, according Vitruvius, large jars made of clay, similarly resonant with bronze vessels had been used instead of them because of lack of means and very advantageous results had been gained. However, this is all to be said today, according t the available data.

CAVITY RESONATORS

The cavity resonators are analogous of mechanical systems having lumped mechanical elements of mass, stiffness and resistance, because they are small in comparison with the wavelength of sound (4). Sir Rayleigh mentions in his book "The Theory of Sound" that the first investigation was done by Helmholtz in 1862 and named as "Helmholtz resonator" (5). The simple Helmholtz resonator may be discussed in terms of an analogous of simple mechanical oscillator. Such a system consists of a rigid enclosure of volume *V*, a small opening through external medium with radius *r* and length *l*. The gas in the opening moves as a unit and provides the mass element of the system. The stiffness element is provided by the pressure of the gas within the cavity of the resonator, and radiation resistance due to radiation at the opening into the surrounding medium and internal resistance due to friction provide a resistance element of the system. The mass element *m* is (6);

$$m = \rho l' S \qquad \text{(kg)} \qquad (1)$$

where; ρ : volume density of gas (kg/m^3),
l' : effective length of opening (m),
S : cross-sectional area of opening (m^2).
The stiffens element *K* is given;

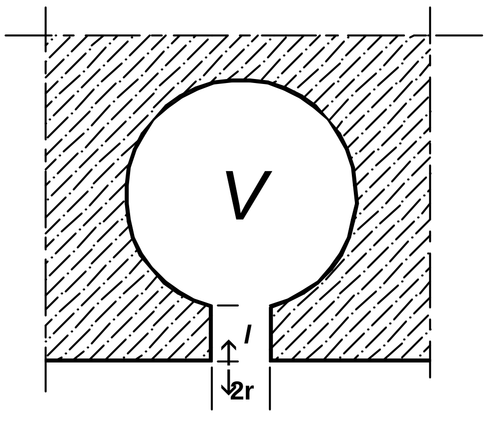

Figure 1. The cavity resonator.

$$K = \frac{\rho c^2 S}{V} \qquad \text{(N/m)}, \quad (2)$$

where ; c : wave velocity (m/sec).
The total resistance element R_t is;

$$R_t = \rho c S \left(\Theta_i + \Theta_r\right) \qquad \text{N sec/m)}, \quad (3)$$

where; Θ_i and Θ_r are the corresponding aperture resistance due to internal friction and the normalised specific radiation resistance of the aperture in order.
After writing the resulting differential equation for the inward volume displacement of the gas in the aperture we get the acoustic impedance Z for Helmholtz resonator as:

$$Z_A = R_A + j\left(\omega M - \frac{K_A}{\omega}\right) \qquad \text{(kg/m}^4\text{ sec)}, \quad (4)$$

where;

the acoustic mass: $M = \frac{\rho l'}{S}$ (kg/m^4), (5a)

the acoustic resistance: $R_A = \frac{R_t}{S^2}$ (kg/m^4 sec), (5b)

the acoustic compliance: $K_A = \frac{\rho c^2}{V}$ (N/m^5), (5c)

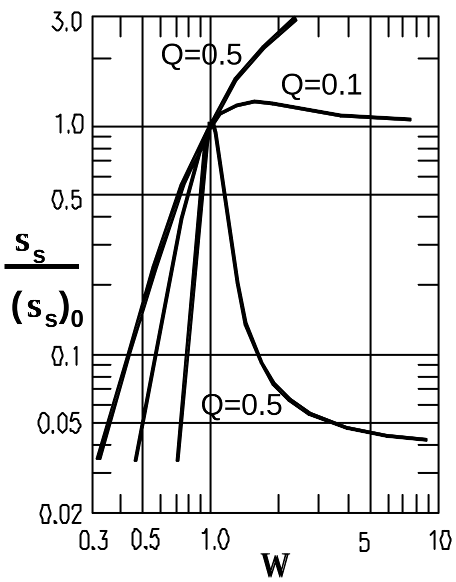

Figure 2. For different values of Q the frequency dependence of the scattering cross section (6).

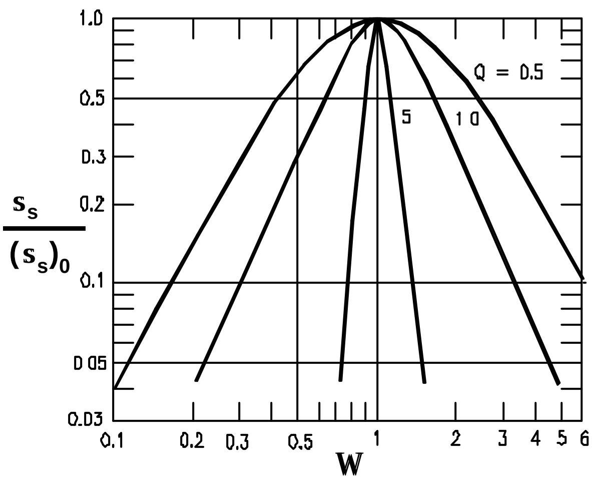

Figure 3. The frequency dependence of the absorbing cross section for different values of Q (6)

For sufficiently low frequencies, Ingard gives the powers scattered (W_s) and absorbed (W_a) by a resonator in a free field as (6):

$$W_s = SP^2\Theta_r / 2\rho c|\zeta|^2 \qquad \text{(watt)}, \qquad (6a)$$

$$W_\alpha = SP^2\Theta_i / 2\rho c|\zeta|^2 \qquad \text{(watt)}, \qquad (6b)$$

where; ζ: The total normalised specific impedance of the aperture, which is;

$$\zeta = \left(\Theta_i + \Theta_r\right)_0 \left[1 - iQ\left(\Omega - 1/\Omega\right)\right]$$

where; $Q = \frac{k_0 l'}{\left(\Theta_i + \Theta_r\right)_0}$,

Ω: the frequency ratio of angular frequency to angular frequency at resonance (ω/ω_0),
k_0: the angular wave number at resonance frequency,

The corresponding scattering (σ_s) and absorbing (σ_α) cross sections are:

$$s_s = \frac{\Theta_r}{|z|^2} S \qquad (m^2), \qquad (7a)$$

$$s_a = \frac{\Theta_i}{|z|^2} S \qquad (m^2). \qquad (7b)$$

The frequency dependence of the scattering cross section and absorption cross section is plotted as a function of Ω for different values of Q by Ingard are given in figure 5 and 6 in order.

CAVITY RESONATORS IN ANATOLIA

The use of cavity resonators in Anatolia goes back to antique Greece, and in the time they became a traditional application, especially in worship buildings, mosques. It is known that other sound systems have also been used, especially during Seljuks and principalities period in Anatolia. Sound channels from music room to patient rooms in a hospital building named Gevher Nesibe Sultan Darüþþifasý (Kayseri, 1205) have been seen. The use of music for therapy in that hospital is also known. The cavity resonators have also been seen in old Kayseri houses. Palamutoðlu house is one of them. The resonators are installed at corners of joining walls and ceiling, where critical points for normal modes of rooms are, especially for oblique modes. Such jars (resonators) can easily be seen at the dome of Yelli mosque at Peçin, which a city of Menteþoðullarý Principality (1340-1400), and the mosque is from that period. These examples show that used technology was developed and became traditional elements of buildings to solve inconvenient acoustical properties of rooms and especially domes.

OTTOMAN PERIOD

Acoustic properties of mosques designed by famous Turkish architect Sinan (known as Sinan the Architect) lived in sixteenth century AC have been investigated. Seven (two big and five medium size in volume) of them have indicated as pilot mosques. The reverberation times of the mosques were measured at the beginning of the research. Except at low frequencies for two big mosques, Suleymaniye Mosque (Istanbul, 1550 – 1557) and Selimiye Mosque (Edirne, 1568 - 1574), measured results were proper enough for enclosures having such big volumes (9). After having proper results by these measurements the acoustical technology applied by him was investigated. Especially the cavity resonators, among the acoustical systems applied by him, were elaborated as an example of the most developed systems in acoustics. So, this result led us to investigate evolution and development of cavity resonators.

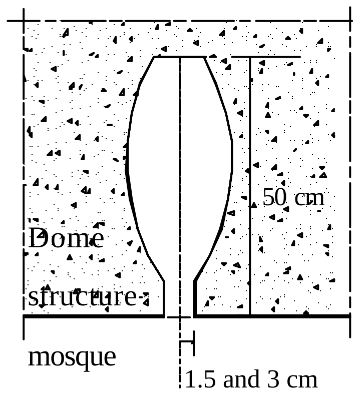

Figure 4. The cross section of the resonator at the dome of Blue Mosque

As it has seen in Sinan's mosques cavity resonators have used prevalently. During the project mentioned above, 75 resonators have been restored at the dome of Blue Mosque., which are terracotta vessels. A group of them have small opening with radius, 1.5 cm, and the others 6 cm (Figure 4). An approximate estimation gave 100-120 Hz for resonant frequency of the resonators with small radius, and 18O-2OO Hz for the others. Some of them were blocked with pales then plastered, the others were blocked with plaster.

This research is concentrated on Sinan's three big mosques, because of getting insufficient reverberation times at low frequencies in two of them. Naturally during the restoration completed recently at Sehzade Mosque (Princes' Mosque), 144 resonators were restored. It is written in the building records (book number 88) of Suleymaniye Mosque that 255 sebu (small jar) have been bought and installed (with open aperture through inside) in the dome and at the corners to improve reflection of sound. It is also added that 510 akce (currency of the period, 2 akce for each) have been paid for them (7). But, only 64 apertures of resonators were counted at the dome of Suleymaniye from the floor level. In fact, the original wall and ceiling decoration of the mosque painted over in 19th century in a manner reflecting Ottoman taste of century. This alien decoration was scraped off, and the original designs of the mosque were revived during the extensive restoration between years 1961 – 1967 (8). But, nothing has been mentioned about the resonators those were not seen. On the other hand, it is mentioned that a great number of the resonators at the dome of Selimiye Mosque were blocked with bricks and then plastered with gypsum (as done before) during the last restoration, this explains the fast prolongation of the reverberation times at low frequencies. So, result is blocked and not working resonators, and problems on sound energy decay and acoustic properties at low frequencies. The reverberation time measurements yielded expected results for other four mosques. The apertures of cavity resonators at domes were seen from the floor level in them. This datum easily explains the long reverberation times at low frequencies for those two big mosques, and also shows efficiency of cavity resonators on acoustical properties of the rooms.

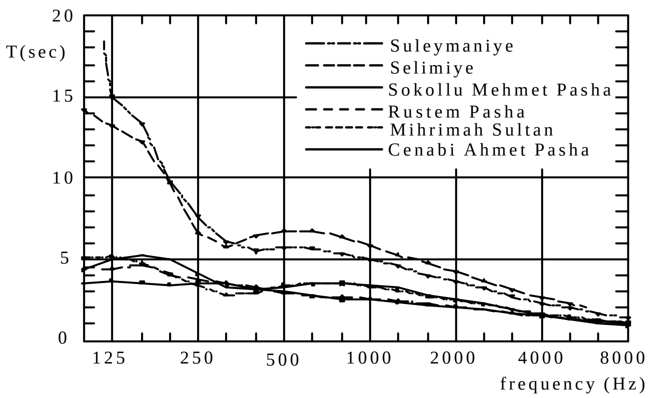

Figure 5. The measured reverberation times of the mosques

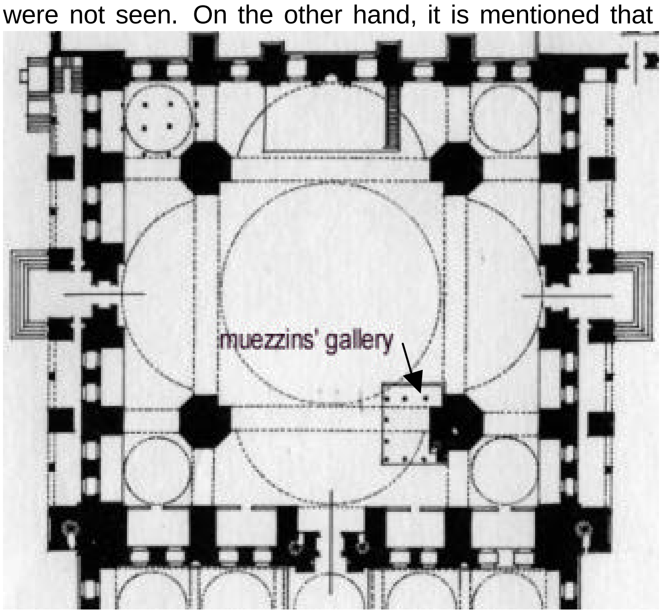

Figure 6. The plan of Sehzade mosque

After all discussion written above, analysis of the plan graphics of the three big mosques showed us improvement on Sinan's acoustical concept during the design process of them. Sehzade Mosque is the first built one with 50 000-m^3 volume (Figure 6.). In such a mosque sound energy is produced by a group of muezzins and they seat on a muezzin gallery. Sinan installed such a gallery adjacent to the pillar at southeast in the mosque. But, in such a big volume without any reinforcement, a big chorus can, only produce the necessary sound energy for sufficient sound quality. It is obvious that, a group of muezzins' sound would be insufficient. When designing Suleymaniye Mosque, which has bigger volume (nearly 80 000-m^3) than Sehzade Mosque, Sinan noticed the problem (Figure 7). So, he installed muezzins' gallery near to the mihrap, adjacent to the pillar at northeast in

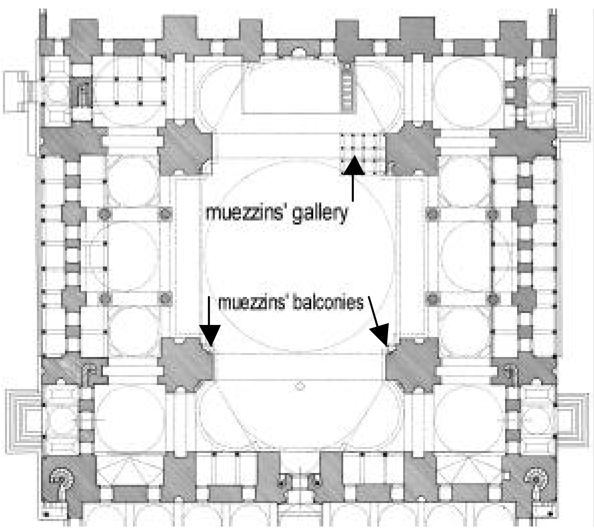

Figure 7. The plan of Suleymaniye mosque

the mosque and added muezzins' balconies adjacent to other three pillars. Muezzins at those balconies would repeat the main group's speech. However, this application increased the problems while decreasing the intelligibility.

Sinan designed a total space at Selimiye Mosque to overcome problem, and reinforced the efficiency of total space by sound. He installed muezzins' gallery under the dome, and also installed the cavity resonators at the dome and at the corners. So, sound energy re-radiates from resonators through congregation. He also defines space by sound energy with this method.

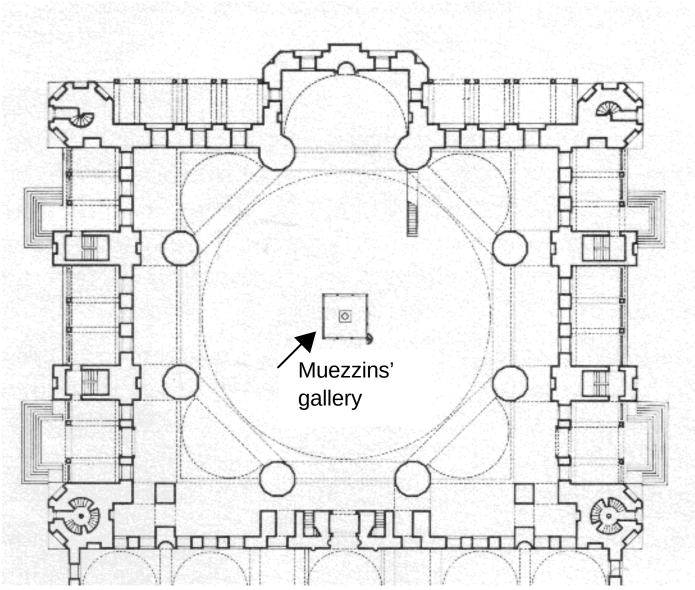

Figure 8. The plan of Selimiye Mosque

CONCLUSION

In room acoustics unwonted reflections and standing waves cause problems especially at low frequencies. It is obvious that use of cavity resonators can easily overcome such problems by proper installations. They scatter the incident energy causing re-radiation of it in all direction. The investigation showed that the technology of cavity resonator is an inheritance from ancient civilisations. The written datum points out this reality too. On the other hand, the cavity resonators have been used prevalently in Anatolia. The used technology has been developed by years. Especially, they have been used successfully at domes of worship buildings to solve inconvenient properties of them.

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