INVESTIGATION OF ACOUSTICAL CHARACTERISTICS OF HÜSREV AĞA MOSQUE AND İBRAHİM ÇELEBİ MOSQUE IN MANİSA, TURKEY

Fatma YELKENCİ SERT [*] ***, Özgül YILMAZ KARAMAN*** [**]

ABSTRACT

From past to present, the single-domed mosques, one of the most important building types for neighborhood, are generally used for daily worship. Although there are many studies on the architectural features and historical processes of single-domed mosques, it is observed that there is no comprehensive inventory of the acoustic conditions for them. It is important to evaluate acoustic conditions of historical mosques, which are accepted as cultural heritage, to identify the interventions that adversely affect these conditions and to suggest the restoration solutions for transmission them to next generations.

In this study, acoustical measurements were taken two historical single-domed mosques in Manisa in order to characterize their acoustical quality and identify the effect of single dome on their acoustical parameters. They have the similar plan schema, a central dome and built in the same historical period. Reverberation time (T30), definition (D50), clarity (C80), STI and SPLA as objective room-acoustic indicators are presented for sample mosques. Hüsrev Ağa Mosque has estimated volume of 725 m^3 and İbrahim Çelebi Mosque with estimated volume of 855 m^3 [2]. The acoustical field measurements are performed for empty mosques in accordance with ISO 3382-2:2008 [3]. The values of $T30_{unoccupied}$ are 2.1 s for Hüsrev Ağa Mosque and 1.9 s for İbrahim Çelebi Mosque in the middle frequencies. T30 values for similar volumes with samples are higher than the optimum range (0.5 – 1.0 s) [1]. Although measured T30 values are good for the musical version of the Holy Quran, they are so high for praying mode and damage to the intelligibility of speech.

(spatial impression) in the mosques is recommended between 1.2 and 1.25, is 1.4 in Hüsrev Ağa Mosque and 1.05 in İbrahim Çelebi Mosque [4]. SPL-A is measured with 6 dB difference among receiver points for both. It shows that desirable consistent sound pressure level distribution is provided in

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* Res. Assist., Dokuz Eylül University, Department of Architecture, İzmir, Turkey.

** Assoc. Prof., Dokuz Eylül University, Department of Architecture, İzmir, Turkey. The bass ratio, which is the optimum values for creating the desired sense

volumes. In mid frequencies, measured C80 values are suitable for each function [5]. D50 values are under 50% (recommended) in mid frequencies. Mean values of STI in mosques are lies between 48% to 58% which means a "Fair" speech intelligibility [6]. In conclusion, mosques were suitable for musical version of Holy Quran. However, the speech intelligibility is damaged by high T30 values. For the improvement of T30 values, restoration of historical mosques with original materials should be encouraged.

Keywords: Room acoustics, Historical Structures, Manisa, Mosque

1. INTRODUCTION

The mosque is one of the most important building types for Muslims which is used for religious rituals such as prayer, Qur'an recitations, Khutba and sermon, etc. Historical mosques have an important position in the society having historical significances besides religious importance. The acoustical characteristics of mosques, considered as cultural heritage, are very important. There is a significant relationship between the cultural heritage building and its acoustics. Some studies on mosques focused on acoustic evaluations and comparisons in mosques and examined them through historical and modern examples (Abdou 2003, Carvalho and Monterio 2009, Carvalho and Freitas 2011, El-khateeb and Ismail 2007, Elkhateeb at al. 2016, Ismail, 2013, Kayılı 1988, Suarez et al. 2005, Sumatera et. al. 2014, Sü and Yılmazer 2008, Sü Gül et al. 2014, Topaktaş 2003, Weitze et al. 2002).

The single-domed mosques, one of the most important building types for neighborhood, are generally used for daily worship. Although there are many studies on the architectural features and historical processes of them, it is observed that there is no comprehensive inventory about their acoustic conditions. It is important to evaluate acoustic conditions of historical mosques, which are accepted as cultural heritage, to identify the interventions that adversely affect these conditions and to suggest the restoration solutions for transmission them to next generations. The case studies are chosen from Manisa which has many cultural heritages, especially mosques belong to Ottoman Empire.

The aim of study is to draw out single domed mosque through analyzing the acoustical characteristics on samples. Hüsrev Ağa Mosque and İbrahim Çelebi Mosque are chosen due to have similar geometrical features to analyze the effect of different materials on acoustical conditions. Moreover, to examine the effects of materials (used inside surfaces of mosques) on the objective acoustical parameters by comparing samples is another aim of study. In literature, most of researcher collects data for studies by using computer simulation program or field measurements. The sample mosques are evaluated by utilizing field measurement (DIRAC) and computer simulation techniques (ODEON). In conclusion, the study has given the results that material features on wall surfaces which is influential surface area affect the acoustic conditions of a mosque and changing type of plaster affect the mosques' acoustical conditions.

2. CASE STUDIES; MANİSA MOSQUES

Manisa, whose history resides to the Palaeolithic period, is an important settlement named Magnesia and Sipylum in the antique period in Turkey. Manisa had an important position in the historical period because it was one of the cities to be sanjak in the Ottoman period where princes were educated and managed. Many important buildings were built in Manisa such as mosque, library, school, Turkish bath, commercial building, etc. Because the members of sultanate with princes and the people who are responsible for the princes' education dwelled in this city (Acun 1999).

In the scope of study, two historical single domed mosques are selected to evaluate acoustical conditions. The mosques examined in present study have same geometrical features (volume, radius of dome, the transition elements) to investigate the effect of different material usage on the acoustic characteristics of mosques.

2.1. İbrahim Çelebi Mosque and Architectural Features

The mosque was constructed in 1549, has the similar plan schema with Hüsrev Ağa Mosque. The volume is a bit bigger than other mosque with an estimated volume of 852 m^3. The structure has a main dome with diameter of 8.6 m. The mosque has a floor area of 86.9 m^2. The mosque as a whole is built on a masonry system by using brick and stone like the other mosque. The walls have approximately thickness of 1.20 m. The main dome is located on octagon hoop supported by wall. The transition from the walls to octagon hoop is provided four pendentives. The walls are covered by painted plaster. Applied wooden panels on the interior walls are at the height of 0.6 m. The pulpit and mimbar are made of wood. The floor is covered by carpets. The loge woman takes part at the north of volume and located on the upper floor carried by wooden pillars. This area is separated from main worship area by perforated wooden panels. The three sectional narthex is on the north of mosque is elevated from the ground and covered by glass surfaces.

2.2. Hüsrev Ağa Mosque and Architectural Features

The building, was built in 1555, has a square plan (9.14 x 9.14 m) [10]. The mosque has a floor area of 83.5 m^2. The mosque has an estimated volume of 724 m^3. The mosque is covered with a single dome. The main dome of mosque has a diameter of 9 m. The transitions from walls to dome are provided by pendentives. The dome is placed on octagonal pulley. The walls of mosque are made of rubble stone, bricks, the corners of walls are made of cut stones, and the domes and minaret are made of bricks. The walls have approximately thickness of 1.08 m.

The worship area for woman is located on upper floor which is separated by perforated wooden panels. The sermon chair and mimbar are made of wood, mihrab is plastered. The floor of mosque is covered with carpet. The mosque is resembled to İbrahim Çelebi Mosque in the architectural sense by some studies in the literature (Acun 1999).

3. RESEARCH METHOD

3.1. Field Measurements

In order to evaluate the acoustic characteristics of selected mosques, DIRAC Room Acoustics Software (Type 7841 v.5.5) was utilized for collecting impulse responses for receiver points. Acoustical field measurements were held by daytime for unoccupied condition in accordance with ISO 3382-2:2008. Fan and air conditioning systems were set to off during the field measurements. The omni power sound source was located at the front of the mihrab and 1.50 m from the floor to represent the position of the Imam while he is talking and giving orders to prayers. The receiver points were placed in the main worship area and women worship area at 0.85 m representing the height of the ear of a prayer with sitting position on the floor. The measured values of the objective acoustical parameters (Background Noise Level, T30, C80, D50 and STI) for selected mosques are evaluated in 'results' section of this study.

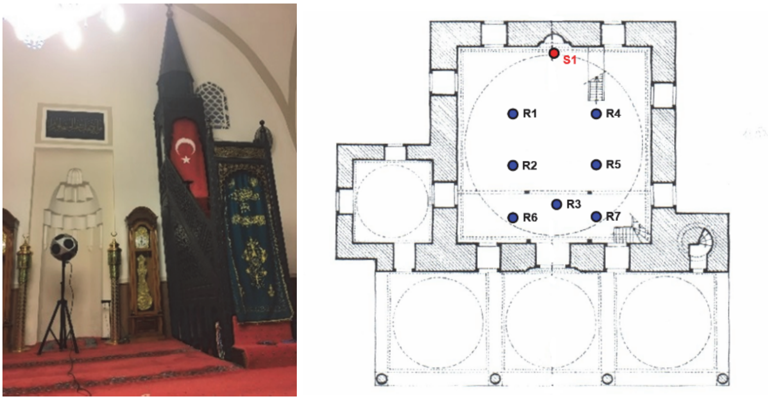

Figure 1. Interior view of İbrahim Çelebi Mosque and position of sound source (S) and receiver points (main worship area; R1, R2, R3, R4, R5 upper floor for women; R6, R7)

Figure 2. Interior view of Hüsrev Ağa Mosque and positions of sound source (S) and receiver points (main worship area; R1, R2, R3, R4 upper floor for women; R5, R6)

3.2. Acoustic Simulations

To test the differences of present and original states; simulation model of İbrahim Çelebi Mosque was done by utilizing ODEON Acoustic Simulation Program. ODEON is used for mosque to analyze the effect of dome to the reverberation time of volume. Furthermore, the importance of historical plaster is discussed in relation to original state in literature (Sü Gül, 2019). It is possible to evaluate the effects of these interventions on the acoustical features by ODEON Software. The 3D model of mosque is carried out in SketchUp and then it is imported in ODEON Software.

Odeon model is utilized to test the acoustic conditions of original state with historical plaster or current plaster and with/ without dome. The materials listed in Table 1 are applied to room surfaces in calibration process (Table 1) (Tavukçuoğlu et al. 2011). As a result of this process, JND for T30 values for simulated and measured ones is kept under 5% which is suggested (Table 2) (Koutsouris et al. 2016).

Table 1. Sound absorption coefficients of materials used in simulation models

İBRAHİM ÇELEBİ MOSQU	sound absorption coefficients								materials
	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz	
wall and dome surfaces (for original state)	0,10000	0,12000	0,25000	0,23000	0,29000	0,33000	0,33000	0,33000	historical plaster tested in 30% humidity (Tavukçuoğlu, Aydın & Çalışkan, 2011)
wall and dome surfaces (for current state)	0,11000	0,11000	0,08000	0,07000	0,06000	0,05000	0,05000	0,05000	Concrete block with or without plaster, painted
floor	0,08000	0,08000	0,08000	0,30000	0,60000	0,75000	0,80000	0,80000	9 mm tufted pile carpet on felt underlay
windows & dividing panel	0,18000	0,18000	0,06000	0,04000	0,03000	0,02000	0,02000	0,02000	Large pane of glass
wooden surfaces	0,42000	0,42000	0,21000	0,10000	0,08000	0,06000	0,06000	0,06000	Thin plywood paneling (3063)
perforated wooden surfaces (mimbar, divided panel for women worship area)	0,28000	0,28000	0,22000	0,17000	0,09000	0,10000	0,11000	0,11000	8 mm wood veneer on 50 mm studs
panels for Imam's room	0,18000	0,18000	0,06000	0,04000	0,03000	0,02000	0,02000	0,02000	Large pane of glass
marble	0,01000	0,01000	0,01000	0,01000	0,01000	0,02000	0,02000	0,02000	Marble slabs

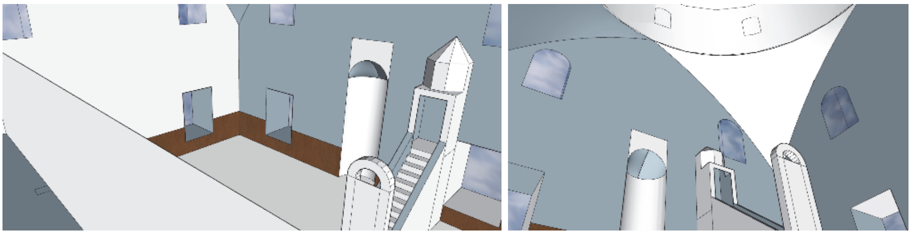

Figure 3. ODEON model of İbrahim Çelebi Mosque

To investigate the effects of using the dome or flat roof; the models of mosque are tested by using ODEON. The source is located in front of mihrab set at a height of 1.5 m. One receiver point (R1) for two types of mosque are placed at a height of 0.85 m representing the seating level. The materials for all surfaces are chosen as 30% absorbent to evaluate the effect of different covers.

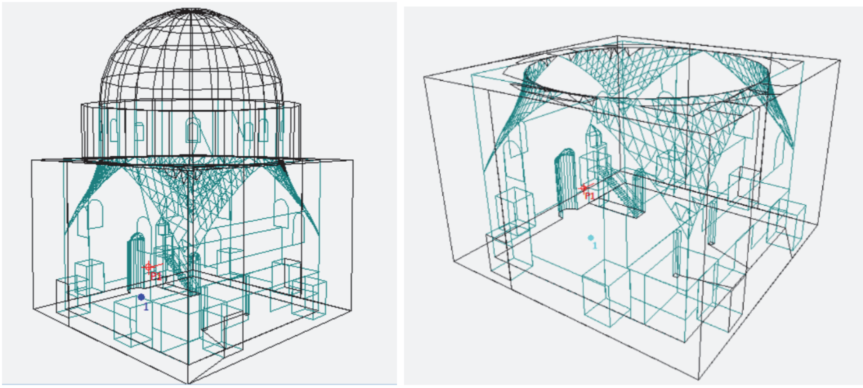

Figure 4. Simulation models of two types of cover for İbrahim Çelebi Mosque

4. RESULTS

4.1. Field Measurement Results

To summarize the field measurement results for mosques, T30 values are shown in Figure 5. It can be seen that; T30 values are mostly around 2 s in mid frequencies. Hüsrev Ağa Mosque has longer reverberation times and is more suitable for musical rituals than other one. However, İbrahim Çelebi Mosque provides better speech intelligibility because of having a nearly flat distribution reverberation line at low frequencies.

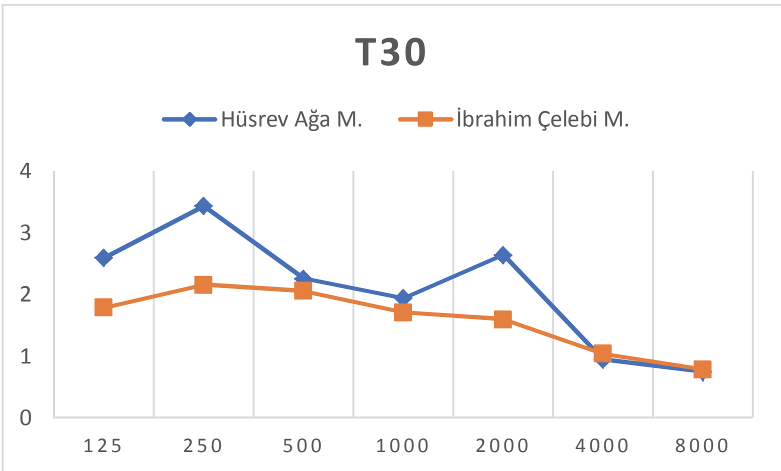

Figure 5. Average T30 results for sample mosques for frequencies from 125 to 8000 Hz

The bass ratio, which is the optimum values for creating the desired sense (spatial impression) in the mosques is recommended between 1.2 and 1.25, is 1.4

in Hüsrev Ağa Mosque and 1.05 in İbrahim Çelebi Mosque (Kuttruff 2009). SPL-A is measured with 6 dB difference among receiver points for both. It shows that desirable consistent sound pressure level distribution is provided in both volumes.

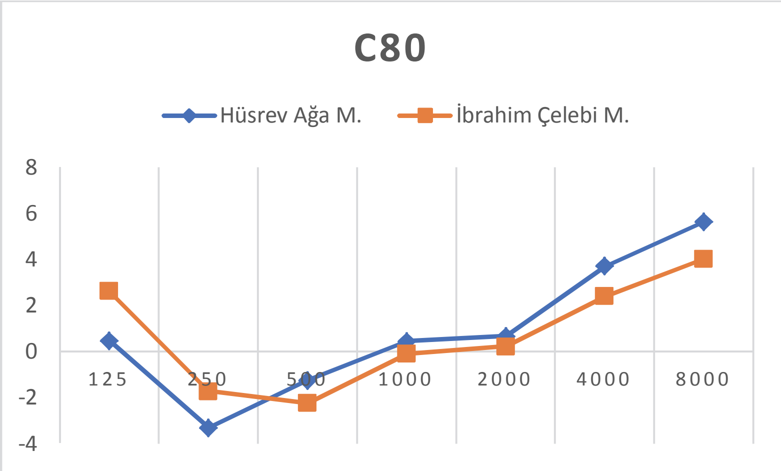

Figure 6. Average C80 results for sample mosques for frequencies from 125 to 8000 Hz

In mid frequencies, C80 values should be between 0 – (-4) dB for music and between (-2) – (+2) for speech (Figure 6). Measured C80 values for İbrahim Çelebi Mosque is between 0 – (-4) dB, for Hüsrev Ağa Mosque is between (-2) – (+2) dB in mid frequencies.

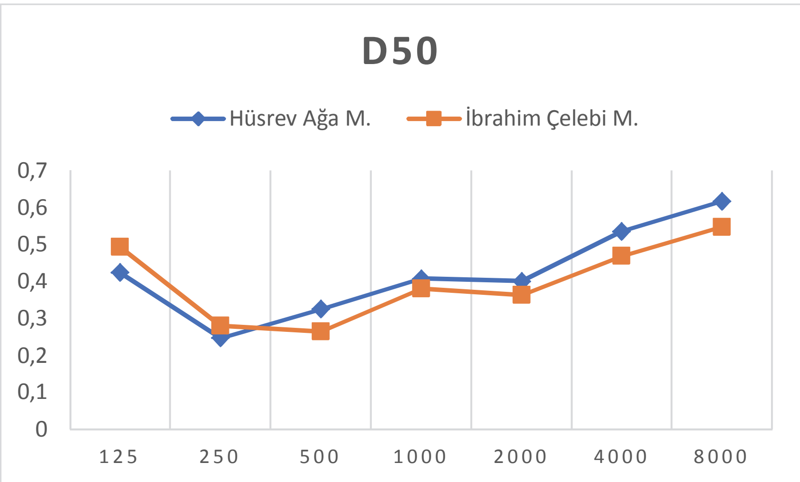

Figure 7. Average D50 results for sample mosques for frequencies from 125 to 8000 Hz

D50 values related to subjective speech intelligibility for both mosques are given in Figure 7. Measured values are found under 50% (which is recommended in literature) in mid frequencies.

STI values related speech are around 0.52 for both mosques, which can be evaluated as "fair". The background noise levels that affect speech intelligibility with reverberation time are measured as 26.4 db(A) for Hüsrev Ağa Mosque, 29.3 db(A) for İbrahim Çelebi Mosque. It is expected that background noise should be between suggested interval limits for good speech intelligibility. The interval limits vary according to the function of building. In the literature, NC25-30 is the recommended noise interval for religious buildings (Beranek 1989). Knudsen and Harris emphasized in their book that the religious buildings have the necessity for insulation from outside noise. They added the noise of inside doesn't exceed 30 db for religious buildings (Knudsen and Harris 1967).

4.2. Simulation Results

Results for evaluate present and original states for İbrahim Çelebi Mosque;

To evaluate the present state of mosque, the walls and dome surfaces are covered by current plaster in ODEON model. Besides this, Historical plaster is used for these surfaces to investigate of original states of mosque. The original state of the İbrahim Çelebi Mosque is arranged as that the wall and dome surfaces with historical plaster. In mid frequencies, the sound absorption coefficients of historical plaster are defined as in the range of 0.23 to 0.29 (Tavukçuoğlu et al. 2011).

Table 2. T30 results of measured and simulated (for original and present state) mosque

İBRAHİM ÇELEBİ MOSQUE							
T30 (s)	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Field measurement	1.78	2.15	2.05	1.70	1.59	1.03	0.78
Odeon (present state)	1.60	2.29	2.06	1.66	1.43	1.21	0.76
Odeon (original state)	1.53	1.05	1.01	0.73	0.53	0.50	0.42

According to the simulation results, JND for T30 values for simulated and measured ones is kept under 5% which is suggested (Table 2). The usage of historical plaster reduces T30 values in overall frequency spectrum. Using sound absorbing materials in the mosque caused low T30 values at high frequency for both conditions.

Results for evaluate the effects of type of roof;

Two models for mosque roof types are modeled to evaluate the effects on acoustical conditions. All surfaces for both models are covered %30 absorbent material while source (S1) is in front of mihrab and receiver (R1) is at the center of main worship area with a height of 0.85 m. According to Table 3, if the mosque constructed with flat roof, T30 values would have lower values overall frequency spectrum. It can be seen clearly that the dome gives the interior space for prayers as a spiritual environment for musical activities.

Table 3. T30 results of simulated models with dome and flat roof

T30 (s)	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Odeon (with dome**)**	0.49	0.52	0.60	0.64	0.64	0.63	0.50
Odeon (with flat roof**)**	0.48	0.47	0.47	0.49	0.52	0.47	0.41

5. CONCLUSION

In conclusion, for 500 Hz and 1000 Hz as speech frequencies, T3O values are obtained 2.1 s for Hüsrev Ağa Mosque and 1.9 s for İbrahim Çelebi Mosque on an average. Obtained T30 values are out of the recommended T30 limits for similar volumes (Kayılı 1988, Orfali 2007). These mosques are more suitable for musical version of Holy Quran. However, the speech intelligibility is damaged by high T30 values.

T30 values obtained from the ODEON model, which the historical plaster is used for wall and dome surfaces, are 1.01 s for 500 Hz, 0.73 s for 1000 Hz. They are closer to the optimum limits than present state. For the improvement of T30 values, restoration of historical mosques with original materials should be encouraged. Balanced distribution of reverberation values is desired for all frequencies to provide the speech intelligibility. In this context, Hüsrev Ağa Mosque couldn't balance the T30 values in low frequencies especially 125 Hz according to İbrahim Çelebi Mosque.

Resulted C80 values in mid frequencies for İbrahim Çelebi Mosque is between 0 – (-4) dB, for Hüsrev Ağa Mosque is between (-2) – (+2) dB in mid frequencies. According to suggested values from literature, Ibrahim Çelebi Mosque is found more suitable for musical activities. D50 values are obtained at least 20% for both mosques. However, mosques couldn't be greater than 50% for all frequencies except 4 kHz and 8kHz.

STI parameter values related to speech intelligibility are measured as 0.52 which is defined as "fair". To improve STI values for having good speech intelligibility, the T30 values can be reduced by using some absorptive materials.

Measured background noise levels are in recommended intervals although they are located in the city center surrounded by parks, cafés and shops. Design criterias such as wall thicknesses of mosques, garden walls, used building materials help to have suitable acoustic conditions inside.

The dome is one of basic architectural elements used in mosques. Although concave surfaces create some acoustical problems such as focusing point, it can be seen as a tool for giving spiritual feelings to the mosque. After testing the ODEON models for two types of roof, model with dome obtained bigger T30 values than the flat roof model. The existence of dome can affect other acoustical parameters besides T30.

This study was carried out in order to maintain the documentation of historical mosques' acoustical conditions in the context of intangible cultural heritage. In such buildings, negative interventions that will affect the acoustic conditions as well as visual environment should be prevented. In addition to this, renovation works should be done by suitable materials which are closer to original ones. Besides, further investigation and analysis could be done for the effect of dome on the other acoustical parameters for mosques.

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