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Review on acoustics timeline of Hagia Sophia and Süleymaniye Mosque in İstanbul

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ABSTRACT

Hagia Sophia built in 6th century and Süleymaniye Mosque in 16th century are the two major monuments of İstanbul World Heritage Site. Süleymaniye Mosque has always functioned as a mosque, while Hagia Sophia previously functioned as a church and mosque while currently serving as a museum. Their historical significance as of being cultural heritages and religious use in relation to acoustics have motivated many researchers to test and discuss over their interior sound fields. A comprehensive study is necessitated to assess the acoustical conditions of both structures in relation to their architectural features and interior finish materials and to examine the changes occurred in the acoustical comfort levels due to the main repairs underwent their life time. One aim of this study is to discuss over the acoustical field test results held in different periods by comparison of common room acoustics parameters. On the other hand, with their immense scale and multi-domed upper structures both monuments exhibit multi-slope sound energy decay. For that reason, as a step forward relevant acoustical predictors including decay rates are discussed in light of different functional uses and spiritual acoustical needs of such monumental sacred spaces.

Keywords: Diffusion equation model, room acoustics simulations, disproportionate rooms

1. INTRODUCTION

This study investigates two historically significant monuments of İstanbul World Heritage Site. The first monument is Hagia Sophia, which was originally built in 6th century and functioned as a church and later converted to a mosque, while currently serving as a museum. The second monument Süleymaniye Mosque is a 16th century structure. Their historical significance as of being cultural heritages and religious uses in relation to acoustics have motivated many researchers to test and discuss characteristics of their interior sound fields. A comprehensive study is necessitated to assess the acoustical conditions of both structures in relation to their architectural features and interior finish materials and to examine the acoustical changes occurred due to the main repairs undergone their life time. The methodology includes the field tests carried both within the scope of this research as well as the published test results by other researchers. Later on, the multi-slope decay parameter analysis is held within Bayesian framework.

Most of the investigations on sacred spaces have concentrated on the behavior of sound within different religious typologies, as of churches (1), cathedrals (2) or mosques (3), and include discussions on their comparison and acoustical criteria. Mostly the sound field investigations in such sacred structures rely on a single sound energy decay and applies the first 20 or 30dB linear decay of the slope for defining reverberation time. On the other hand, 'room acoustics coupling' has far been investigated for theoretical understanding of convex (non-exponential) sound energy decay characteristics mostly in coupled spaces. For this research it is motivational that convex decay curve which incorporates multiple decays is previously observed in large cathedrals or basilicas, which are composed of interconnected sub spaces (4-6). Thus, another focus of this study is to identify and quantitatively assess the multiple sound energy decays in such super-structures. The basic methodology of multiple sound energy decay investigations is decay parameter estimations that rely on Bayesian formulation (7), over collected field measurement data as discussed in following sections.

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2. MATERIALS

2.1 Süleymaniye Mosque

Süleymaniye Mosque and Complex (Fig. 1) was constructed in between 1550-1557 in the Ottoman era in İstanbul. The mosque is covered centrally by a single dome which is supported on two sides by semi domes. The two semi domes align with the direction of the mihrab. Side aisles are sheltered by five smaller domes which complete the upper structure. The inner plan of the mosque measures 63 by 69 m. The height of the dome from the ground to the keystone is 47.75 m. The Mosque has an approximate acoustical volume of 75.000 m³. Corner domes are supported by arches in between elephant feet and exterior shell walls. The three side domes sit on arches, each of which is supported by two columns on two rows. Pendentives are utilized to smooth the central dome, secondary half dome and arch connections. *Muqarnases* are located in half dome skirting's and side dome arch transitions, which help to enhance the sound diffusion in mostly curvilinear and concave transition planes by fragmenting the surfaces into much smaller pieces.

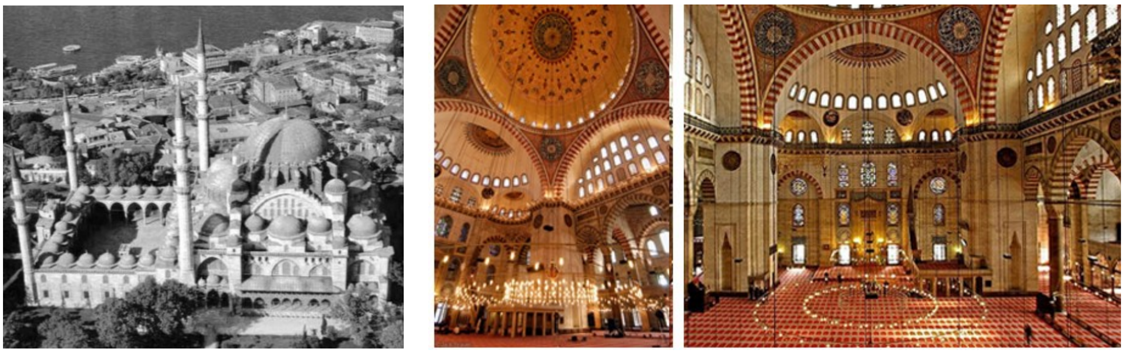


Figure 1. Süleymaniye complex exterior view (on the left) (8), interior views (on the right)

The uniqueness of the building complex comes from abundant source of stone supplies delivered from various ruins of ancient cities all over the world. For its original state, basic interior materials are stone, brick, tile, ceramic pots, plaster, paint, glass and wood. Lime, horasan, fine sand, gypsum, linen and straw are the basic ingredients of plaster layers and seams. Linen is applied in dome plasters (8). In contrast to lavishly painted domes and pendentives in lower zones the stone revetments left relatively bare. The prominent architectural features of the interior are historical columns, marble panels, porphyry discs, great arches, the mihrab, minbar and royal box, stained glass windows and inscriptions. Floor finish of the mosque is carpet with straw backing -which are collected from the finest straws grown in Nile delta- as stated in original documents (9). Carpets had originally been woven in Egypt and Aydın-Tire. Another feature of Süleymaniye Mosque for its original state is the use of Sebu's (clay pots), that are believed to be applied for the function of cavity resonators for the control of excessive low frequency sound content.

Since 16th century, Süleymaniye Mosque hasn't gone through major structural changes. However, there has been couple of major interior material modifications. The initial restorations were held in 19th century. In these interventions basically pen-carved paintings and plasters were modified, which ended up in a totally different material characteristic. At 1840's and 1880's restorations, held by Italian experts, it is recorded that the clay pots were covered and closed and the original dome plasters were modified with gypsum plaster. In 1959-1969 restorations some of the 19th century paintings were removed in order to uncover the original paintings. Prior to 2007-2011 restorations, on stone and wooden surfaces different types of material deteriorations were detected. Damage report prior to 2007-2011 restorations also include structural damage, the damages due to cement-based plastering or seam fills, and damages due to some other inappropriate use of material (8). The cement-based plasters and application of pen wall paintings on these plasters are significant in assessing the changes in acoustical field of the Mosque. During 2011 restorations the samples of original horasan plasters in dome were collected. Tests and analysis were held for obtaining cement free plasters that are compatible with original ones, then applied on renewed plastering and pen-wall paintings. Besides, it is also declared that the mouths of 15 cm width and 45 cm length total 256 clay pot's (Sebu) are opened and cavities are repaired.

2.2 Hagia Sophia

Hagia Sophia had been constructed as a church in between 532-537 in İstanbul during Byzantine time. After the Ottoman conquest in 1453, in the ruling of Mehmet II, it was converted from church to mosque. In 1932 upon order from Atatürk, Hagia Sophia has started to function as a museum. Hagia Sophia has a large interior space, having an approximate volume of 150.000 m³, with many coupled sub-spaces. The sound field of such a volume with dominating geometric and material attributes inspired this study in terms of acoustical coupling investigations. The major figure of Hagia Sophia is an expanded dome basilica: a rectangular building, measuring 73.5 m to 69.5 m, excluding the narthex and the apse, covered by a central dome between two half domes (Fig. 2).

Figure 2. Hagia Sophia an old photograph (10) and interior view *(ayasofyamuzesi.gov.tr)*

The central dome, with an approximate diameter of 32 m, rises 55 m above the pavement of the nave. In order to keep the basilica design on both sides of the central nave, rather than semi domes there are columns, arches and vaults. The domed central space is skirted by two large hemicycles covered by half domes to the east and west. The diameter of these half-domes roughly equals to that of the central dome. These core spaces are separated from side aisles by superposed colonnades, with galleries over the side aisles and inner narthex. The central oval vessel of enclosed space is further expanded by barrel-vaulted spaces that terminate along the building's longitudinal axis of its nave (11). Stone, brick and mortar are the main elements of the above-ground structure including the piers, columns, arches, vaults and dome. The surfaces of all the walls as well as the large supportive piers are covered with polished slabs of veined marble and other colored stone. Most of the original non-figural mosaic decoration of the vaults has remained undamaged at ground level. All surviving figural mosaics are of later date. The floor of this broad space is paved today with large rectangular marble slabs -not the original one which are crushed in 1346- (10-11).

Over the 1400 years of its existence, Hagia Sophia has suffered much damage essentially due to major earthquakes. Three main phases of structural repair and strengthening are recorded. The first repairing phase was in 1317, the second was in 1573 and the third repair was in 1847. The principal work undertaken in 1317 was the construction of new buttresses. In 1573, a new minaret is built in place of one that was to be demolished. In 1847 major works were the rectification of a number of columns in the gallery exedra, the installation of new ties for critical locations, and other repairment at the level of the dome base. Hagia Sophia has also undergone many alterations due to changes in its activity patterns. In conversion from church to mosque, some Christian elements were removed and Islamic additions were introduced. Since pictorial representations are traditionally not permitted in Islam, after 1453 the mosaics were gradually covered up, whitewashed or plastered over and hence preserved. The Christian furnishings were removed. In 1847 the sultan commissioned Swiss architects to restore both the fabric and the decoration of the building. During these works all the surviving mosaics were uncovered, and copied in order to provide visual record. Among the Islamic additions apart from four minarets on the exterior, a mihrab was added on the kiblah direction. The minbar was constructed in the same direction. Prayer carpets and banners of victory were hung on the walls flanking the mihrab during the mosque period. The Müezzin's mahfili in the center of the structure and four more galleries in the narthex were added. On the left side of the central nave there still is the preaching pulpit. Imperial Pavilion and Imperial Loge are some other additions which did not exist during the Christian period (10-11). In 1992, a major restoration and consolidation of the mosaics in the dome was started by the Central Laboratory for Restoration and Conservation of Istanbul in collaboration with an international team of experts funded by UNESCO. Not all listed here but many other Hagia Sophia restoration works has taken in its lifespan. Even today the scaffoldings cover a huge space within the interior space for repairment of observable mosaic damages currently due to the water leakage and humidity at the central dome, which also effects the acoustical field measurements to a degree.

3. METHODOLOGY

3.1 Field Measurements

Field tests, within this study's scope, were held in Süleymaniye Mosque on 23rd February 2013, (quoted as METU-2013 in this paper) hours in between 19:30(pm) -3:00(am) at the main prayer hall, and in Hagia Sophia on 25th August 2014 (quoted as METU-2014 in this paper), hours in between 09.00(am) 12.00(am) at ground floor, for both in unoccupied conditions (12-13). Major source locations in Süleymaniye Mosque are one in front of mihrab (S1) and one at müezzin mahfili (S3) (Fig. 3, on the left). The positioning of sound source is important to assess the acoustics of mosque in its traditional use. For coupling research, additional source locations such as one underneath the main dome (S4) and one underneath side corner dome (S2) are tested (13). In order to compare multi-slope decay formation for different locations considering the effects of spatial variations (such as main central space versus underneath side galleries) within Hagia Sophia, three source (S1 - S3) and six receiver (R1 - R6) positions are tested in various configurations (Fig. 3, on the right). Measurement system includes B&K (Type 4292-L) standard dodecahedron omni-power sound source, B&K (Type 2734-A) power amplifier and B&K (Type 4190ZC-0032) microphone covering the frequency interval in between 100 Hz to 8000 Hz. Sampling frequency of the recorded multi-spectrum impulse is 48 kHz. DIRAC Room Acoustics Software Type 7841 v.4.1 is used for signal generation.

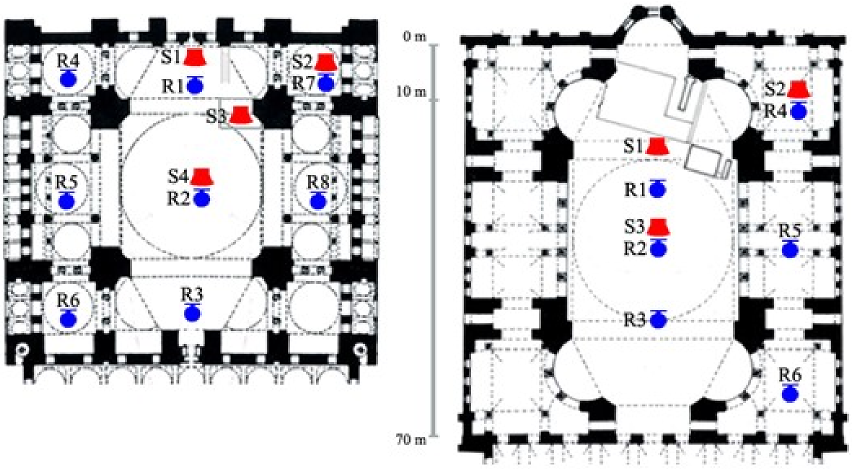


Figure 3 - Plan views with sound Source (in red) and Receiver (in blue) locations of METU- 2013 field tests in Süleymaniye Mosque (on the left) and METU-2014 field tests in Hagia Sophia (on the right)

Other measurements following different restoration periods apart from those held within the scope of this study are also summarized in this section. The first set of measurement (14) in Süleymaniye Mosque was held after 1959-1969 restorations by Gazi University in 1988 (GU-1988). Following field tests were taken by METU (15) in 1996 (METU-1996). The final group of measurements after 1959-1969 restorations, were held in 2000 within the program of EA project namely CAHRISMA (16). Ferrara University (UNIFE-2000) and Denmark Technical University (DTU-2000) took two different measurements. The major restoration and consolidation of the mosaics in the dome of Hagia Sophia has started in 1992. There is no available measured acoustic data in the literature before that period. The measurements have been held in Hagia Sophia after 2000 while restorations were on-going. Previous to Hagia Sophia measurements held in the scope of this research, two other set of data were recorded. Ferrara University (UNIFE-2000) and Denmark Technical University (DTU-2000) hold two different measurements again in the context of CAHRISMA (16) project in 2000.

3.2 Decay Parameter Estimations

The computational analysis methodology of this study employs Bayesian probabilistic inference as an efficient tool (7). Bayesian model-based parameter estimation, describing Schroeder decay function, is used here to determine the parameters of the decay profile, namely "the slopes of decays". Schroeder decay functions are obtained through Schroeder backward integration. Parametric model describing Schroeder decay function is as follows;

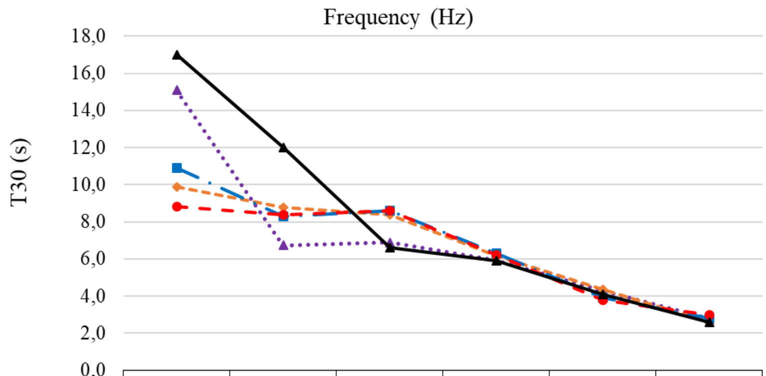
$$H_s(A, T, t_i) = A_0(t_K - t_i) + \sum_{j=1}^{S} A_j \left(e^{\frac{-13.8 \times t_i}{T_j}} - e^{\frac{-13.8 \times t_K}{T_j}} \right) \quad \text{where index } 0 \le i \le K-1$$

Schroeder decay function contains decay parameters of A_j and T_j, where A_j is the linear amplitude parameter and related to the level of individual exponential decay terms, T_j is the decay time associated with the logarithmic decay slope of individual exponential decay terms, with j = 1, 2, …, S, and S is the maximum number of exponential decay terms, also termed as the decay order, A_0 (t_K- t_i) is the noise term, and t_K is the upper limit of integration (12). The question of how many decay slopes are in the energy decay data has always been challenging. As a scientifically rigorous solution Xiang et al. (7) propose to evaluate the Bayesian evidence which automatically encapsulates the principle of parsimony and quantitatively implements Ockham's razor. Bayesian evidence prefers simpler models and penalizes over-fitting, so that it offers effective tools to conduct model selection and comparison going beyond traditional parameter estimation methods. The quantifier is defined to be Bayesian Information Criterion (BIC), which subtracts the penalty of over-parameterized models from the degree of the model fit to the data. In the scope of the energy decay analysis among a set of decay models, the model yielding the largest BIC value is considered to be the most concise model providing the best fit to the decay function data and at the same time capturing the important exponentially decaying features evident in the data. Applying BIC for ranking the competing decay models, such as double-slope, triple-slope, and even quadruple-slope decay models, is found appropriate for data analysis in this study.

4. RESULTS

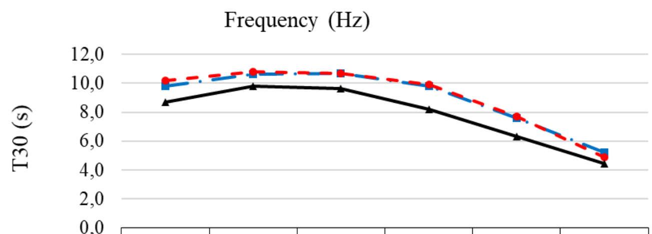
4.1 Field Tests Results and Discussion

The results presented in this section are initially for comparative analysis due to several restorations of the case structures recorded in different years by different research groups. With an aim of assessing the acoustical effects of previous restoration works in Süleymaniye Mosque the field measurements taken in 2013 (METU-2013) are compared with previous field test data. The common acoustical parameter measured and assessed in all field tests is the reverberation time (T30). Some previous literature recommends reverberation times of 4.8 s for speech frequencies (500Hz, 1000Hz, 2000Hz) and 2.8 s in broadband as a higher limit for mosques with similar volume. According to Fig.4 all of the field tests indicate very long reverberation times, higher than recommended ranges for the mosques for unoccupied condition. Especially, 125 Hz is very problematic considering the intelligibility of speech; which will be even worse when electro-acoustic system is on, as in today's applications. Both of the first measurements taken by GU-1988 with analogue equipment and the final measurements taken by METU-2013 with digital equipment and with an impulse length of 22 seconds, indicate 15 to 17 seconds of T30 values at 125 Hz. Thus, it could be stated that 2007-2011 renovations have not significantly affected the T30 values at 125 Hz, which are still very high and above the acceptable limits for Mosque function. The comparative analysis of field test results indicate that the 2007-2011 restorations resulted in slightly positive decrease in reverberation time at 500 Hz, whereas in overall the values are still higher than the recommended ranges. The attempts for removing cement-based plasters, and application of plasters that are compatible with historical lime-based plasters, as so declared, are constructive but not yet efficient acoustical interventions; especially in control of low frequency sound content.



	125	250	500	1000	2000	4000
Süleymaniye GU-1988	15,1	6,7	6,9	5,9	4,3	2,8
Süleymaniye METU-1996	9,9	8,8	8,4	6,2	4,4	2,6
Süleymaniye DTU-2000	10,9	8,3	8,6	6,3	3,9	2,8
Süleymaniye UNIFE-2000	8,8	8,4	8,6	6,2	3,8	3,0
Süleymaniye METU-2013	17,0	12,0	6,6	5,9	4,1	2,6

Figure 4. Comparison of T30 field test results of Süleymaniye Mosque by GU-1988, METU-1996, DTU-2000, UNIFE-2000, METU-2013 and AU-2013 in field tests, in 1/1 octave bands from 125 Hz to 4000 Hz.



	125	250	500	1000	2000	4000
Hagia Sophia DTU-2000	9,8	10,6	10,7	9,8	7,6	5,2
Hagia Sophia UNIFE-2000	10,2	10,8	10,7	9,9	7,7	4,9
Hagia Sophia METU-2014	8,7	9,8	9,6	8,2	6,3	4,5

Figure 5. Comparison of T30 field test results of Hagia Sophia by DTU-2000, UNIFE-2000 and METU-2014 in field tests, in 1/1 octave bands from 125 Hz to 4000 Hz.

In Fig. 5, Hagia Sophia filed test results are compared for different years. Hagia Sophia field tests held in 2000, highlight that T30 values in overall are higher than field test results of METU-2014 measurements. The presence of additional architectural constructions due to ongoing restorations within the space during METU-2014 measurements has resulted in a drop of 1 to 2 seconds in overall frequency spectrum. On the other hand, the trend of the T30 over octave bands is similar for all Hagia Sophia field tests. It is known that, there are no major architectural or form modifications in between 2000 and 2014 in Hagia Sophia restorations. However, there is no available data before 1992 restorations to compare the basic alterations of Hagia Sophia, especially in regards to changes in its function, and to discuss on the success of cleaning of the mosaics. In its current state, the T30 results obtained in recent years by different research groups indicate very high reverberation times within the mega-structure, which might be much proper in its original use of church considering liturgical music but not for a mosque function. Mid and low frequency T30 average of around 9 s and high frequency averages around 5 s creates a unique aural environment and has the potential to provide acoustical field conditions in relation to coupled spaces. Non-exponential sound energy decay is one outcome of Hagia Sophia's architectonic language, which is briefly discussed in the following section.

4.2 Multi-slope Sound Energy Decay Investigations

In this section multi-slope energy decay analysis results are presented for some selected test positions for Süleymaniye Mosque and Hagia Sophia (Table 1). In overall test positions Süleymaniye Mosque provides greater number of decay slopes, mostly double slopes, in comparison to Hagia Sophia. Conversely, for certain source and receiver configuration, the triple slope occurrence in Hagia Sophia is drastically higher than its occurrence in Süleymaniye Mosque. This instance is due to those specific measurement locations, which are both at side aisles under gallery. In those locations the sound source and receiver are together positioned at virtually separated zone (side aisle) with lower natural reverberation, as of in a typical coupled space scenario. Here, the coupled space or secondary volume which provides energy feedback is the main nave underneath the central dome axis of Hagia Sophia.

Table 1. Bayesian estimated number of decay slopes per 1/1 octave bands calculated from impulse responses obtained at different source (S) and receiver (R) configurations in Süleymaniye Mosque and Hagia Sophia

Süleymaniye Mosque				**Frequency (Hz)**				**Hagia Sophia**				**Frequency (Hz)**			
$S_{\#}R_{\#}$	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	$S_{\#}R_{\#}$	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
S_1R_2	2	2	2	2	2	2	2	S_1R_2	1	1	1	1	1	1	2
S_1R_4	2	2	2	2	2	2	**3**	S_1R_4	2	2	2	2	2	2	2
S_1R_5	2	2	2	2	2	2	2	S_1R_5	1	1	2	2	2	2	2
S_1R_6	2	**3**	2	2	2	2	2	S_2R_1	2	2	1	2	2	2	2
S_2R_1	2	2	2	2	2	2	2	S_2R_2	1	1	1	1	2	2	2
S_2R_4	**3**	2	2	2	2	2	2	S_2R_5	**3**	**3**	2	2	2	2	2
S_2R_6	2	2	2	2	2	2	2	S_2R_6	**3**	**3**	**3**	**3**	2	**3**	2
S_2R_8	2	2	2	2	2	2	2	S_3R_1	1	1	1	2	2	2	2

Due to the larger span of arches in Süleymaniye Mosque, the side aisles behind those major arches supporting the central dome are not restricted as much as arcades separating side aisles of Hagia Sophia. The smaller arches of Hagia Sophia with a basilican plan layout create much defined coupling apertures. This architectural layout causes triple slope decays underneath side aisles as in cathedrals. On the other hand, the occurrence of multiple sound energy decay in Süleymaniye Mosque can be explained by the central dome as an energy accumulation center versus the carpeted floor as a sound attenuation surface. In terms of multiple-decay formation, the absorption introduced by carpet floor finish versus a reflective upper structure provides an un-diffused sound field. Consequently, the sound energy density fragmentation in Süleymaniye Mosque is much obvious in comparison to Hagia Sophia's for its main space underneath the central dome. Thus, the overall number of decay slopes is greater in Süleymaniye Mosque than it is for Hagia Sophia. A further investigation of multiple-slope decay formation in effect of architectural features in such mega-structures is held by sound energy flow analysis through diffusion equation modelling and detailed in another study (17).

5. CONCLUSION

This study initially summarizes the geometric and material features of two world heritage buildings in relation to their interior sound fields and presents the architectural interventions due to different restorations. The architectural significance and the immense enclosed main volume and sub-volumes attracted many acousticians and various field tests were held in different years including those held within the scope of this study. The T30 values as a common parameter measured in all field tests are compared for different years in order to understand the acoustical outcomes in relation to restorations and also to document this archival information. Another discussion point, briefly mentioned in this study, is that the sacred monuments provide not a single decay with a single reverberation time but multiple sound energy decays. For that reason, the use of single slope metrics to define reverberation is debatable in analysis and understanding of the decay characteristics within mega-structures especially those with multi-domed upper shell typology. The significance of multiple-decay, in form of early and late energy, is that the early decay enhances clarity or definition of sound thereby improving intelligibility, while the late decay contributes to the reverberance that complements the spiritual needs. Thus, the unusual sensation (hearing) of sound in such monumental sacred spaces may be explained by overlapping decay curves and their acoustical outcomes.

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