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## **3aAAb4. Acoustical design of Turkish Religious Affairs Mosque**

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The new Turkish Religious Affairs Mosque(DIB) with its prayer capacity and outstanding volume is the largest neo-classic mosque project of the past decade built in Ankara, Turkey. The Mosque is also one of unique examples of its scale for which the room acoustic design is applied in its design phase. Acoustical design of DIB Mosque is critical considering speech and music related activity patterns held in such religious spaces. Interior surface forms and materials of walls, floor, flat ceilings and dome are studied simultaneously with the architectural design as early as in the concept phase. Impedance tube is used for testing alternative materials for specifying sound absorption characteristics of reliefs and perforations. Computer simulation is applied as an acoustical design tool and estimations are held by ODEON v.11.23. Objective acoustical parameters including reverberation time, speech transmission index and A-weighted sound levels are assessed with and without sound reinforcement systems for fully and partially occupied mosque conditions. Auralizations are held for imam and muezzin in different forms of religious call out to prayers. Evaluation of the space indicates that the optimized acoustical field is proper for intended functions of use in a mosque and satisfies desired tranquil environment.

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## INTRODUCTION

Mosque as of a building typology is an enclosure for Islamic worship, which is essentially a good subject matter for room acoustics with its finely defined forms and involved activity patterns. In acoustical terms, the general activity patterns are the intelligibility of conveys of imam in weekly Friday's sermon and the speech-music interpolation of imam's commands in a daily preaching activity called *namaz*. In architectural design of a mosque, the desired acoustical criteria must be incorporated within a visual aesthetic for the success of a mosque which satisfies the spiritual aspects of worship.

Analysis of the previous literature on mosque acoustics reveals some common architectural features and corresponding acoustical outcomes. Mosques have all hard and reflective interior finishes for walls and ceilings including ceramic tile, glass, wood and stone, except for the carpet floor finish together with frequent use of prayer mats and rugs. Thus, speech intelligibility in a mosque is hampered by reverberation and/or echoes, due to both large sizes of traditional mosques and sheltering elements mostly of either domed or vaulted geometry<sup>1-4</sup>. Electronic sound reinforcements are applied in new generation mosques, while this is not an exclusive solution for inappropriate acoustical comfort levels of a worship space, without a proper architectural background<sup>5-7</sup>. All studies support the idea that wisely detailed building envelope and proper interior design with a keen consideration on acoustics are the key elements for the high-quality acoustic performance of mosques.

Although there is an increasing interest on mosque acoustics research, in compare to investigations on churches the field is still growing. More input is necessary in relation to acoustical design criteria and design parameter formation of Mosques. Most of the researches utilize scale model and computer simulation techniques in mosque renovations or experimentation of architectural features in mosques<sup>8-11</sup>. Assessed acoustical metrics are basically reverberation time (RT60, T30), sound pressure levels (SPL-A) and speech transmission index (STI). The objective of this paper is to document the acoustical design steps in realization of Turkish Religious Affairs (DIB) Mosque, which is aimed to be an acoustically performing space with respect to architectural concept. Acoustical design of the mosque is held using computer simulation technique. Basic acoustical design considerations in this study are defined to be materiality of the main prayer hall and optimization of acoustically absorptive, reflective and diffusive surfaces for the benefit of acoustical comfort levels.

Granted by Religious and Social Services Charity of Turkey, the construction of DIB Mosque has been inaugurated in 2008 in Ankara and still is in progress. The prayer halls have a capacity of 5000 prayers within a total built area of 80,000 m<sup>2</sup> of the complex. DIB Mosque has a neo-classical style with a single sheltering dome supported by 4 arches and pendentives as transitional elements. The sheltering dome possesses the largest sizes in Turkey when compared to other traditional and new generation mosques that are supported by 4 elephant feet. The dome sits on a square plan layout of 33 m x 33 m. Arches carrying the load from dome to ground have a maximum height of 18 m. The height of the dome from floor is 33 m (Fig. 1).



**FIGURE 1.** DIB Mosque; exterior view from construction phase (left), 3D interior render (right)

## ROOM ACOUSTICS CRITERIA AND DESIGN

Acoustics tops the list of major comfort parameters in mosque design together with other building physics factors like lighting and HVAC. Speech intelligibility is the primary acoustical concern and necessitates suitable designation of volume, geometry of the main space and appropriate use of acoustically absorptive and diffusive materials as finish surfaces. In view of that, acoustical design is integrated into the architecture in the early stages of

design of DIB Mosque. The defects due to traditional domed mosque typology has long been known and in past centuries precautions are even taken by application of clay pots in form of Helmholtz Resonators by ‘Sinan the Architect’ in his grand Ottoman mosques for fixing the undesired acoustical environment. As in previous cases the problems caused by the geometric symmetry and acoustic foci that causes echoes or harsh reflections together with excessive reverberation due to large volume have to be solved in the case of DIB Mosque.

Initially the acoustical design criteria are set for assessing objective acoustical measures. Reverberation time has been used as the paramount technique for discovering the acoustic characteristics of room’s environment<sup>12</sup> and, in the case of the holy mosque, clues on intelligibility and sound aesthetics. Speech is the primary activity in a mosque, and intelligibility of the speech is the major concern, particularly when imam conveys his messages at Friday’s sermon from above *minbar* and/or for imam or preacher of his informative speech from the pulpit. In relation to that, STI has been promoted for predicting speech intelligibility through impulse response. Another related metric is sound pressure level, which is the most commonly used indicator of the acoustic wave strength, correlating with human perception of loudness. The A-weighted sound level (dBA) is the single number measure of loudness that ignores low-frequency sound energy content similarly to the human ear<sup>13</sup>. In a closed acoustical environment as in mosques’ prayer hall, the distribution of SPL-A is significant both in terms of indicating the strength of sound in each receiver location and also in illustrating how evenly sound is distributed throughout the space.

Although the speech intelligibility is utmost priority, a mosque is not a classical speech room as a conference hall or auditorium. Acoustical environment of a mosque should satisfy the spiritual aspects of worship, while enabling the most proper environment for perception of imam and *müezzin* conveys. The space in function of mosque should not be acoustically dull, as well as not excessively reverberant. Accordingly, the volume effect and dome function are considered together in defining acoustical design guidelines<sup>11</sup>. Adopted acoustical parameter limits are listed in Table 1.

**TABLE 1.** Optimum limits for acoustical parameters in relation to volume and mosque function

Acoustical Parameter	Optimum Limits	Just Noticeable Difference (JND)
Reverberation Time (T30 average of 500Hz and 1kHz)	1.8 s-2.2 s	%5 (0.1 s)
A-Weighted Sound Pressure Level (SPL-A)	max.-min. level difference < 10 dB	2 dB
Speech Transmission Index (STI for single source)	> 0.5	0.05

The architectural style and concept of the DIB Mosque is dominated by the huge dome element with a circumference center outside the physical limits of the space, which could not be reformed for the sake of acoustics. For that reason, in minimizing acoustical defects caused by domed geometry and large volume, the dome is treated by an absorptive surface finishing. The absorption by the dome, composing one of the largest interior surfaces, is not only for reducing the effects of sound focusing but also for dropping the global reverberation times within the main prayer hall. The major intervention to the dome material design is application of perforated gypsum panels with mineral wool backing concealed behind surface carvings/reliefs out of molded gypsum. Attaining both sound absorption and scattering functions to the dome surface aims to distract acoustical symmetry and consequently to provide much even distribution in interior sound field that is free of sound foci and echoes.

In addition absorption attained to dome, walls are treated with micro-perforated wood and perforated gypsum boards are applied on cove ceilings. For increasing diffusion and scattering characteristics in specific frequency ranges, specific surfaces such as stained glasses and marble wall claddings are either sand blasted and/or textured in special carvings. A final acoustical intervention is in selection of carpet floor finish material, which composes the largest absorptive surface within a mosque prayer hall. Different alternatives are tested by impedance tube method for obtaining the highest acoustical performance.

## METHODS

### Impedance Tube Measurements

Impedance tube tests are basically carried out for predicting sound absorption coefficient values of carpet floor finish materials and micro-perforated auxiliary space wall finishes, where the data could not be provided by the

manufacturer. Acoustic tests are conducted with respect to ISO 10534-2 Standard and performed with SCS Kundt Tube. For low frequency values (50 Hz – 1200 Hz), S.C.S.9020B impedance tube with 100 mm diameter, for high frequency values (800 Hz – 6300 Hz), S.C.S.9020B impedance tube having 28 mm diameter are used. Data input and acquisition are done by 01dB-dB4 AREVA data acquisition board. Sound absorption values are obtained from SCS software. Absorption test configuration includes a sound source generating plane waves for a wide frequency range, measurement tubes with two microphones and test samples. Data acquired from the microphones are processed via “FFT Transfer Function” method in order to obtain sound reflection and absorption coefficient values of the test material. All these values are measured in 1/3 octave band frequencies and the results are assessed between 125Hz and 4000Hz corresponding to reliable ranges to be applied in following computer simulations. Physical properties of tested carpet floor finish and the resultant sound absorption coefficients over octave bands are given in Figure 2. Physical properties of tested micro-perforated wood finishes and the resultant sound absorption coefficients over octave bands are listed in Figure 3.

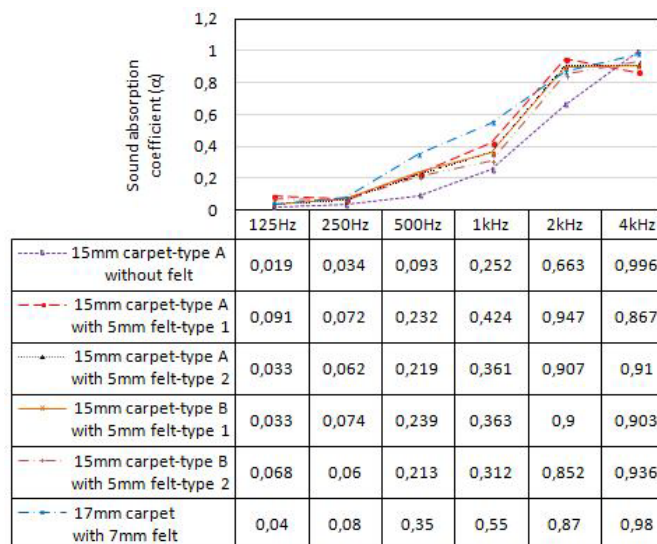


FIGURE 2. Impedance tube measurement results and physical properties of tested carpet samples

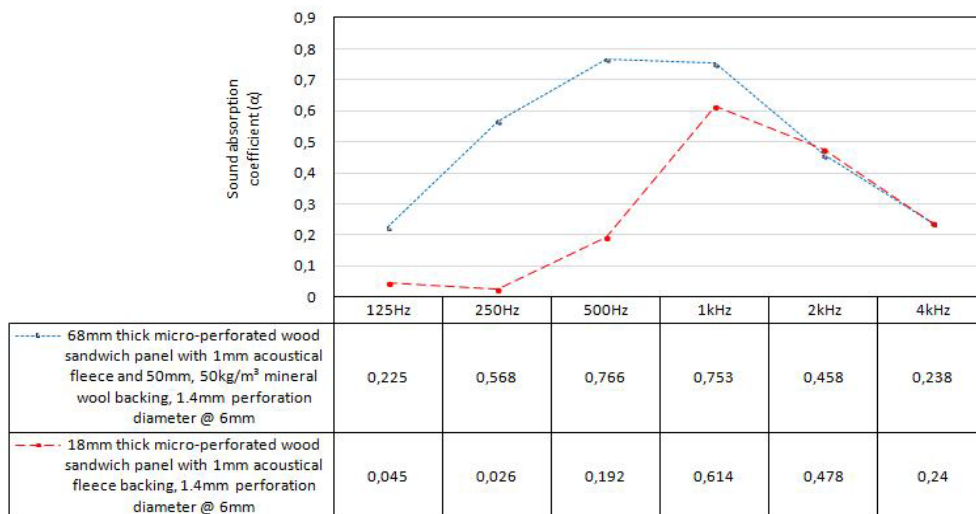


FIGURE 3. Impedance tube measurement results and physical properties of tested micro-perforated wood panel samples

Impedance tube measurement results indicate that sample of 17 mm carpet having a surface density of  $1.5 \text{ kg/m}^2$  with 7 mm felt backing possesses the highest sound absorption coefficient values in average over octave bands. 68 mm thick micro-perforated wood (1.4 mm perforation diameter @ 6 mm) sandwich panel with 1 mm acoustical fleece and 50 mm thick,  $50 \text{ kg/m}^3$  dense mineral wool backing has higher sound absorption capacity, specifically in low to mid frequencies, in compare to 18 mm thick sample with no mineral wool backing. Samples with highest sound absorption characteristics are recommended to be applied as floor and flat wall finishes. The measured sound absorption coefficient values are attained in material list of ray tracing software to relevant surfaces.

### Ray Tracing Model Analysis

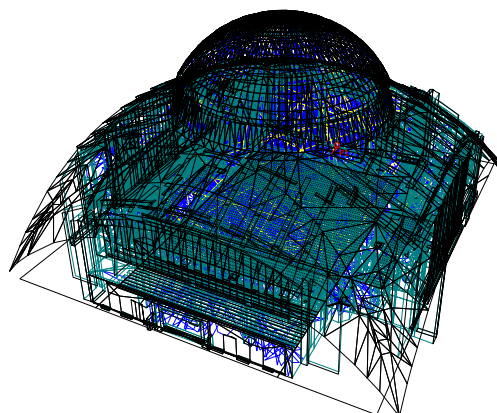
Computer aided simulation is adapted as a major design tool. The use of computer simulation in the analysis of acoustical properties of a space in design phase prior to the actual construction has proven practical and reliable as to be an integral part of the architectural design process. Acoustical simulations of DIB Mosque are carried out using ODEON Room Acoustics Software (v11.21). Calculation method of the software relies on a hybrid process combining ray tracing and image source methods specifically applied for either early or late sound reflections. A statistical approach is adopted for modeling the higher order reflections. ODEON uses vector-based scattering in its prediction algorithms by which the reflection from a surface is modified from a pure specular behavior into a diffuse behavior for more accurate results<sup>14-15</sup>.

A graphical model of the mosque is generated in SketchUp to be imported in ODEON room. The simplified model made up of 3-D face elements is comprised of 11,243 plane surfaces. In the process of modification of the geometry the graphical model is preserved in great detail in order to maximize the effects of domes and scattering surfaces, while keeping the limits of minimum surface dimensions dictated by the software (Fig. 4). Estimated acoustical volume of the mosque is  $92,987 \text{ m}^3$ .



FIGURE 4. 3D-OpenGL view of acoustical model

The materials that are applied to room surfaces are listed in Table 2 with corresponding sound absorption coefficient data. Scattering coefficients ranging in between 0.1 to 0.5 are attained to surfaces according to differing surface irregularities. In calculation parameters number of late rays is defined to be 100,000 and the impulse response length is set to 3,000ms. Ray tracing is used majorly in sound path analysis. One omni-directional source is defined in front of *mihrab* at 1.50 m depicting standing imam (Fig. 5). Receiver area is defined in a mapping of rows divided into grids of  $0.90 \text{ m} \times 0.90 \text{ m}$  indicating each person praying. In order to get the results of different acoustical parameters and their distribution throughout the mosque, the maps and cumulative distribution graphs for calculated parameters are obtained for receiver surfaces. NC30 is used in attaining the background noise as it is the given limit appropriate for HVAC system noise of spaces similar in function to mosques. A sound power level of 87 dB is assigned to the omni-directional source representing the naked voice of imam preaching.



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FIGURE 5. Ray tracing model with one source (red) position

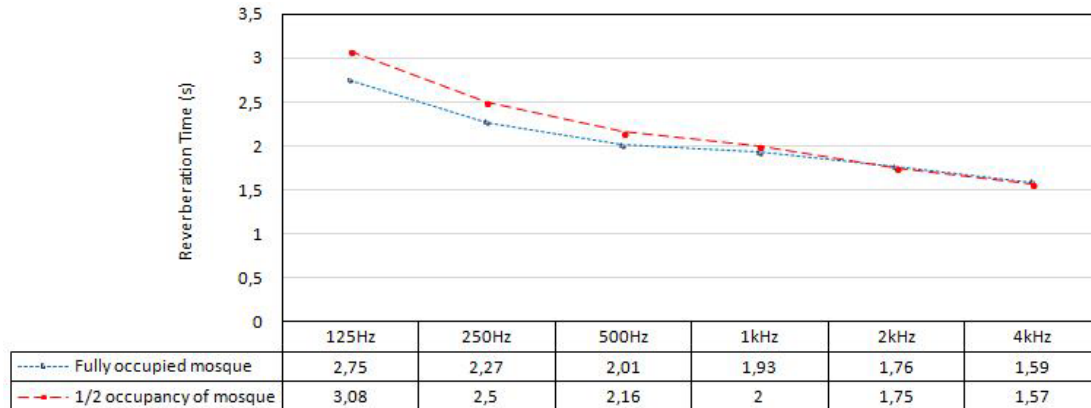
TABLE 2. Sound absorption coefficients of materials applied within mosque interior surfaces

Material Type / Location	Octave band center frequency (Hz)					
	125	250	500	1000	2000	4000
Sand blasted marble / <i>mihrab</i>	0.010	0.010	0.010	0.010	0.020	0.020
Un-perforated wood boards / walls	0.150	0.200	0.100	0.100	0.100	0.100
2 layers of 13 mm gypsum board / flat walls, ceilings and pendentives	0.150	0.100	0.060	0.040	0.040	0.050
Perforated gypsum board; Knauf 6/18R, perforation ratio %8.7, with 400 mm air gap behind, standard fleece and 50 mm thick, 50kg/m <sup>3</sup> dense mineral wool backing / flat cove ceilings	0.400	0.450	0.450	0.500	0.450	0.500
Perforated gypsum board; Knauf 8/12/50R, perforation ratio %13.1, with 65 mm air gap behind, standard fleece and 50 mm thick, 50kg/m <sup>3</sup> dense mineral wool backing / dome	0.350	0.550	0.700	0.700	0.600	0.500
17 mm carpet with 7 mm felt backing / flooring of prayer halls	0.040	0.080	0.350	0.550	0.870	0.980
68 mm thick micro-perforated wood sandwich panel with 1 mm acoustical fleece and 50mm thick, 50kg/m <sup>3</sup> dense mineral wool backing, 1.4 mm perforation diameter @ 6 mm / flat walls	0.225	0.568	0.766	0.753	0.458	0.238
Glazing / standard windows	0.300	0.200	0.140	0.090	0.060	0.040
6 mm textured glass / stained glass decorative panels	0.100	0.060	0.040	0.030	0.020	0.020
Sitting person / prayer rows	0.430	0.490	0.650	0.600	0.590	0.460

## RESULTS

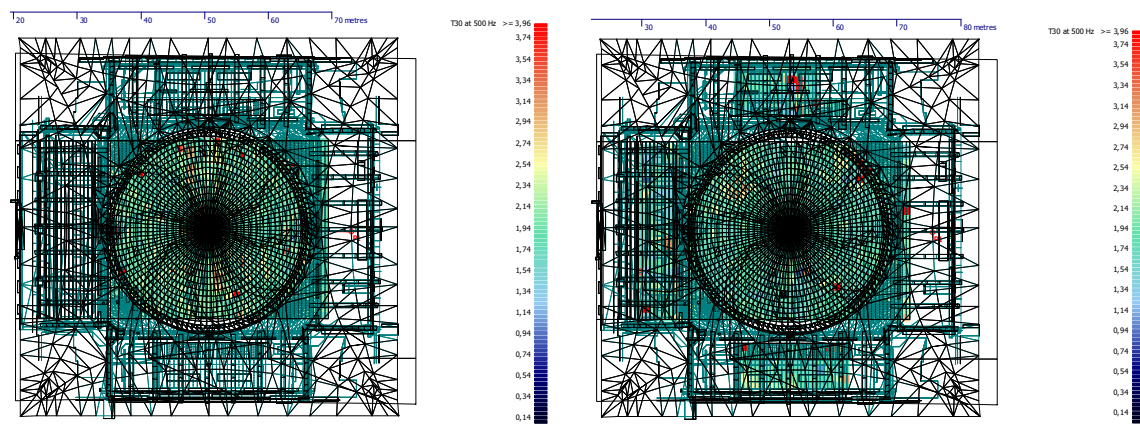
Results are tested majorly for full occupancy of mosque corresponding to Friday's sermon and 1/2 occupancy indicating daily prayer mode. For these two activity patterns reverberation time is assessed as of a primary indicator in analysis of sound field perception. Mosque acoustical simulations of T30 over frequency range are initially estimated as a global average of the interior volume. Distribution maps are obtained for defined grids and maps of 500 Hz are presented, which includes the dominant male speech (imam) frequency content. STI and SPL-A maps are included in the case that electro-acoustic enhancement is on, which are highly dependent upon the speaker quantity and sound power data. The details of electro-acoustic layout and specifications are kept out of this paper, as they are developed by other groups of expertise.





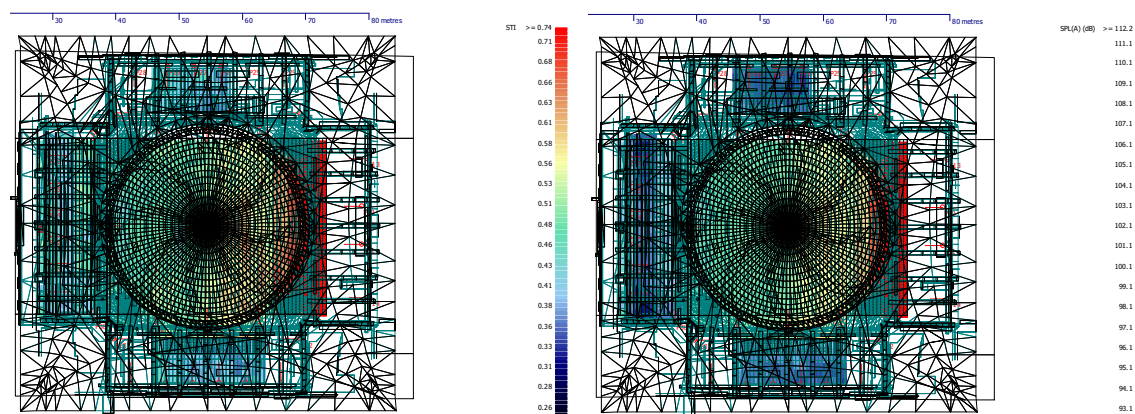
**FIGURE 6.** Global estimates of T30 over octave bands without electro-acoustic enhancement for fully occupied mosque and 1/2 occupancy of mosque

As shown in Figure 6 the fully occupied mosque -indicating the maximum use of capacity in Friday's sermon- has a mid frequency (average of 500Hz and 1kHz) T30 of 1.97 s. The low frequency T30 (average of 125 Hz and 250 Hz) of the same condition is 2.51 s. Thus the bass ratio, which is the average of low to mid frequencies, is 1.27. Global estimate results of daily prayer activity pattern in 1/2 occupancy of the mosque depicting daily prayer mode are given in the same graph for comparison (Fig. 6). According to that, the mosque has a mid frequency T30 of 2.08 s and a low frequency T30 of 2.79 s. The bass ratio for this later condition is 1.34. In compare to full occupancy T30 values get slightly higher in 1/2 occupancy in mid to low frequencies, with a maximum deviation of 0.3 s in 125 Hz. For both activity patterns with differing prayer capacities T30 results are within given criteria range.



**FIGURE 7.** T30 distribution map for 500 Hz for mosque without electro-acoustic enhancement for fully occupied mosque (left), T30 distribution map for 500 Hz for mosque without electro-acoustic enhancement in 1/2 occupancy (right)

In Figure 7, T30 distribution maps of main prayer hall are presented for 500 Hz of fully occupied mosque and 1/2 occupancy of mosque, in sequence. In fully occupied state %60 of audience area has a T30 (500Hz) of 2 s. For %10 of receiver locations maximum T30 is 2.6 s and for the same statistical range minimum T30 is 1.7 s. For 1/2 occupancy of mosque %50 of prayer floor has a T30 (500 Hz) of 2.15 s. For 10% of receiver zones the maximum and minimum T30 values are 2.5 s and 1.95 s, in sequence. The percentile of over range values is considerably low and acceptable for such domed geometry and large sizes of mosque interior.



**FIGURE 8.** STI distribution map for fully occupied mosque with electro-acoustic enhancement (left), SPL-A distribution map for fully occupied mosque with electro-acoustic enhancement (right)

STI distribution maps are obtained in operation of electro-acoustic enhancement and for NC30 (Fig. 8). %50 of receiver zone has STI of 0.50 and over. The range is in between 0.42-0.70 in overall. The minimum values of STI are observed in side aisles or have architectural restrictions in the direct sound path, both of which are out of sight of imam situated in front of *mihrab*. For most receiver points STI indicates ‘Good’ speech intelligibility within mosque, for fully occupied condition with electro-acoustic enhancement. As given in Figure 10, SPL-A distributions within fully occupied mosque with electro-acoustic enhancement ranges in between 98-108 dB. Parameter just satisfies the maximum allowable sound pressure level difference of 10 dB among prayer/receiver locations.

In presence of electro-acoustic enhancement auralizations are held for three different positions of source for full occupancy. First location is in front of *mihrab* depicting *namaz* orders of imam in daily prayer mode. Second is on top of *minbar*, where imam conveys his Friday’s sermon and third is on top of *mahfili*, where *müezzin* performs the call for pray in a sort of musical recital.

## CONCLUDING REMARKS

Acoustical parameters are assessed in design phase by acoustical simulations for fully occupied and 1/2 occupancy of mosque corresponding to most common activity patterns. In developed acoustical design three main objective criteria in mosque acoustics are satisfying the limits for reverberation time, intelligibility of speech and even distribution of sound for the majority of prayer/worshipper zone. T30 over frequency is relatively flat in comparison to mosques with big domes and large volumes indicating balanced sound absorption over octave band spectrum and better intelligibility of speech. In occupied condition the maximized number of worshippers attending Friday prayer slightly improves the T30 values in compare to 1/2 occupancy, by effecting the total sound absorption inside the mosque. Proper values of T30 together with sound level enhancement by an electro-acoustic system application, STI values indicate ‘Good’ levels of intelligibility rating for majority of receiver/prayer positions. Within the mosque sound distribution throughout the usable prayer zone/floor indicates few hot and dead spots, which are tolerable considering the volume of the prayer hall and dome size. Parameter value drops/increases are consistent with the distance from the sound source.

Two important subjective acoustical parameters for the mosque function are envelopment and warmth. Envelopment is both related to the lateral reflections and spaciousness, which is provided by the increased volume due to the additional space of dome structure at the upper zone. Warmth is provided by the longer low frequency content that is necessary to create desired spiritual atmosphere for religious recitals. The latter necessitates low RT values at mid to high frequencies allowing optimal speech intelligibility for Imam’s Friday’s sermon when enabling both warmth and high intelligibility. DIB Mosque satisfies warmth and augmentation of male voice with bass ratio values over 1.25. This envelope of RT characteristic with respect to frequency is found to be instrumental for mystic feeling to develop among the worshippers<sup>16</sup>.

The smooth interaction of architecture and acoustics professions is highly significant in creation of acoustically functioning worship spaces as in case of DIB Mosque. Major acoustical design decision in this study is the application of perforated gypsum board with mineral wool backing concealed behind reliefs/lettuce work on dome



surfaces, working for both sound absorption and scattering. Sound diffusion and scattering within the mosque have also improved by textured marble and glass surfaces. The intervention on dome geometry has improved the acoustical asymmetry and by that has reduced the focusing effects that could otherwise lead to uneven distribution of sound with acoustical defects. Sound absorption within dome sphere and additional absorption by micro-perforated wood wall panels and perforated gypsum ceiling panels have augmented the sound attenuation by upper enclosure and consequently have resulted in controlled reverberation times. The absorptive carpet floor finish is specifically studied by impedance tube measurements, as it composes the largest surface, to which the sound absorption role could be attained. The balance of sound absorption over frequency ranges are obtained through the use of multiple types of sound absorptive materials applied in sufficient amounts and in proper locations. Considering all the studied parameters it could be stated that Turkish Religious Affairs (DIB) Mosque is an optimum space for mosque activities.

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